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Development of Criteria for Extension of Applicability of Low Emission, High Efficiency Coal Burners: Second Annual Report

Energy and Environmental Research Corp.
Irvine, CA

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Research Triangle Park, NC

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DEVELOPMENT OF CRITERIA FOR EXTENSION OF APPLICABILITY OF LOW EMISSION, HIGH EFFICIENCY COAL BURNERS:
SECOND ANNUAL REPORT

by

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Coal		Stationary Sources	21D
Burners		Distributed Mixing Burners	13A
Combustion			21B
Properties			14G
Nitrogen Oxides			07B

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ABSTRACT

This report describes the second year's effort under EPA Contract 68-02-2667 which is concerned with the development of criteria for the evaluation and applicability of low-emission, high-efficiency coal burners. The report describes progress in three major areas: (1) Bench Scale Studies, (2) Distributed Mixing Burner Development, and (3) Comparison with Commercial Practice. The bench scale studies are concerned with an investigation of the impact of fuel characteristics on fuel NO formation during the combustion of pulverized coal. Although fuel NO emissions generally increase with increasing fuel nitrogen content, coals with the same rank and similar nitrogen contents may produce markedly different fuel nitrogen levels. Preliminary results indicate that a simple procedure which evaluated reactive volatile nitrogen could be used to assess the impact of coal type on fuel NO formation. The body of data relating to the development of the distributed mixing burner has been reviewed and data has been obtained with both single and multiple burners. No operability problems were encountered with different fuel types but NO emissions were fuel dependent. Several commercial burners have been tested satisfactorily in the test facility. One gave severe flame impingement. Carbon monoxide emissions were generally higher and nitrogen oxide emissions were slightly lower than commercial practice.

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1.0 SUMMARY

This is the second annual report describing progress on EPA Contract 68-02-2667 "Development of Criteria for Evaluation of Applicability of Low Emission, High Efficiency Coal Burners." The significant accomplishments in this effort were:

- Bench Scale Studies. These studies were concerned with the development of a data base on the effect of coal type on NO formation and the definition of optimum conditions for minimum NO formation under idealized fuel/air contacting. Although fuel NO emissions increased with increasing coal nitrogen content, coals with the same rank and similar fuel nitrogen content produce markedly different fuel NO levels. Preliminary results suggest that a simple procedure which evaluated reactive volatile nitrogen could be used to assess the impact of coal type on NO production. Studies on the optimization of the conditions in the fuel-rich stage of a staged system indicate that minimum gas phase nitrogen species (HCN + NH_3 + NO) does not necessarily give minimum emissions after burnout.
- Distributed Mixing Burner Development. The body of data relating to the development of the distributed mixing burner has been reviewed and summarized. Single and multiple burner data has been obtained for two different fuels. The distributed mixing concept can be operated with different fuels and it appears that emission levels are sensitive to fuel type. However, no attempt was made to reoptimize the burner for different fuels.
- Comparison with Commercial Practice. Several commercial burners have been tested in the large watertube simulator. All the burners performed satisfactorily and produced stable flames. However, one burner gave a flame length which caused severe flame impingement on the rear wall of the test furnace which makes comparison with field practice invalid since such severe impingement could not be tolerated. Carbon monoxide emissions produced with the commercial burners were slighly higher than those usually found in field

operating units and nitrogen oxide emissions were slightly lower.

The results obtained to date suggest that further work is required in the following areas:

1. Investigations to eliminate the need for outboard staged air ports by optimizing the fuel injection air distribution system.
2. Further investigations to define the optimum conditions to minimize NO formation during staged combustion.
3. An investigation into the impact of combustion modifications on the fate of other trace species in coal such as sulfur and inorganic particulate.

2.0 THE GENERALIZATION OF LOW EMISSION COAL BURNER TECHNOLOGY

Nitrogen oxide formation in pulverized coal flames can be reduced by using the burner to control the rate of fuel air mixing in order to minimize fuel nitrogen conversion. This annual report describes the progress on EPA Contract 68-02-2667, "Development of Criteria for Extension of Applicability of Low Emission High Efficiency Coal Burners." The program has the following objectives:

- Expand the fuel capability of low NO_x burners to include the major types of solid fossil fuels projected for use by the utility industry.
- Explore additional burner concepts and configurations that show potential for improving the emission and thermal performance of pulverized coal burners.
- Determine the effects of multiple burner configurations that are encountered in utility boilers.
- Provide for direct comparison between the experimental burners being developed herein and the current state-of-the-art for commercially available coal burners.
- Arrange for coordination of the technology development program with boiler manufacturers and users.
- Provide testing in support of planned application of the burner technology.

A chart is presented in Figure 2-1 which shows the relationship of the various tasks which are planned to meet these objectives. The following sections of this report present data obtained in Tasks two, three and five. This section deals with two aspects of the effort associated with Task 1 - Program Definition; these are:

- Fuel Selection
- Measurement Protocol

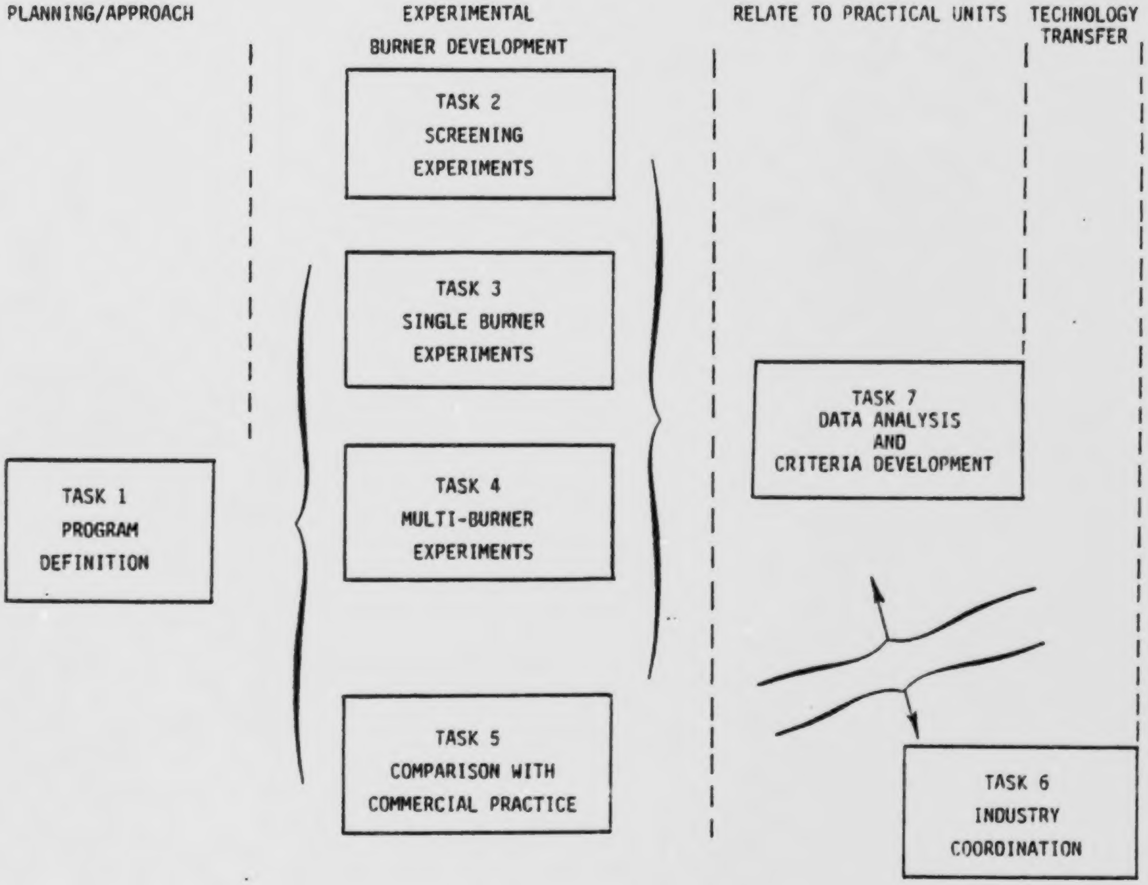

PLANNING/APPROACH
EXPERIMENTAL BURNER DEVELOPMENT
RELATE TO PRACTICAL UNITS
TECHNOLOGY TRANSFER
TASK 1 PROGRAM DEFINITION
TASK 2 SCREENING EXPERIMENTS
TASK 3 SINGLE BURNER EXPERIMENTS
TASK 4 MULTI-BURNER EXPERIMENTS
TASK 5 COMPARISON WITH COMMERCIAL PRACTICE
TASK 7 DATA ANALYSIS AND CRITERIA DEVELOPMENT
TASK 6 INDUSTRY COORDINATION

Figure 2-1. Overall Program Logic.

2.1 Fuel Selection

The generalization of low emission coal burner technology for a wide range of fuels is one major objective of the program. Appendix A lists all the coals acquired to date, the mines from which they were obtained, and a summary of the properties. Figure 2-2 presents a summary of all the coals available (data symbols and identification correspond to Appendix A) showing nitrogen content on a dry, ash-free basis and rank. The solid symbols indicate those coals which have been tested to date. The nitrogen content, on a dry, ash-free basis, ranges from approximately 1.9 to 1.1 for the bituminous coals to .95 - 1.3 for lignites. The fuels selected provide a wide range of properties to study the fuel effects. The sulfur content ranges from approximately 4% (DAF) for Eastern bituminous to less than 0.5% for Western bituminous. The forms of sulfur (pyritic, organic and sulfate) that exist in the various coals are tabulated in Appendix A. It has been suggested that the ratio of oxygen to nitrogen content of a coal impacts the NO_x emission because of oxygen availability. This ratio is relatively low for the older, bituminous coals and gets progressively higher for the younger coals through the lignites as the inherent mixture content increases.

Figure 2-3 shows the geographical location of the coals available for testing on this contract. Most of the major coal seams in the United States are represented in the present program. The Eastern bituminous coals are well represented as are Western bituminous, subbituminous and lignite. More coals from the large Texas-Louisiana lignite seams would be desirable as well as from the mid-Western bituminous deposits. In addition to the United States coals, limited quantities are available from Australia and a brown coal from Germany.

Efforts will be concentrated in the future on the acquisition of other types of solid fuels, such as char, solvent refined fuels, etc. To date a char prepared from a Utah bituminous coal and a COED process gasification char from an Illinois bituminous coal have been obtained.

2.2 Measurement Protocol

One aspect of the program definition task is the preparation of measurements protocol as a guideline to the measurement techniques and procedures

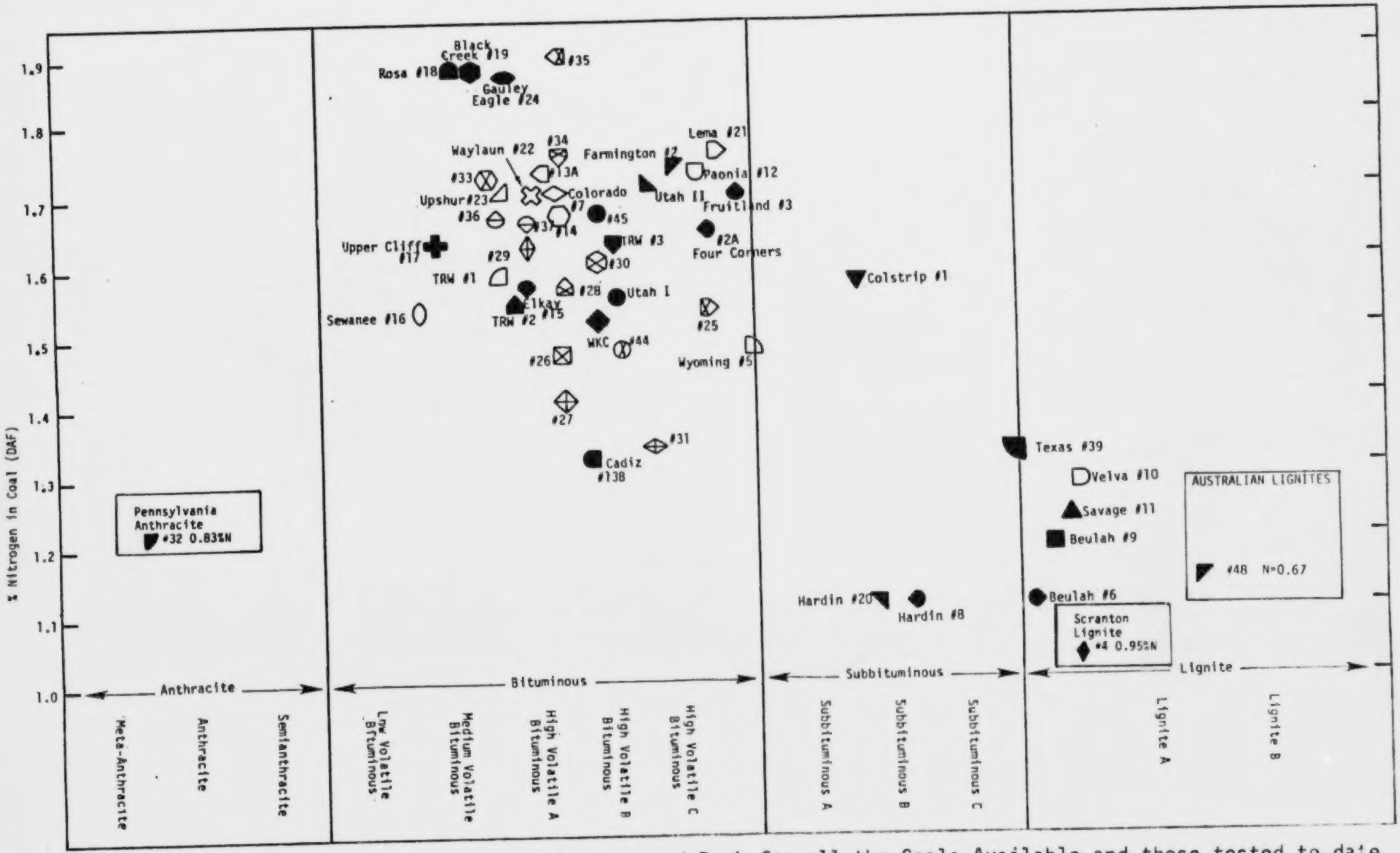


Figure 2-2. Summary of Nitrogen Content and Rank for all the Coals Available and those tested to date.

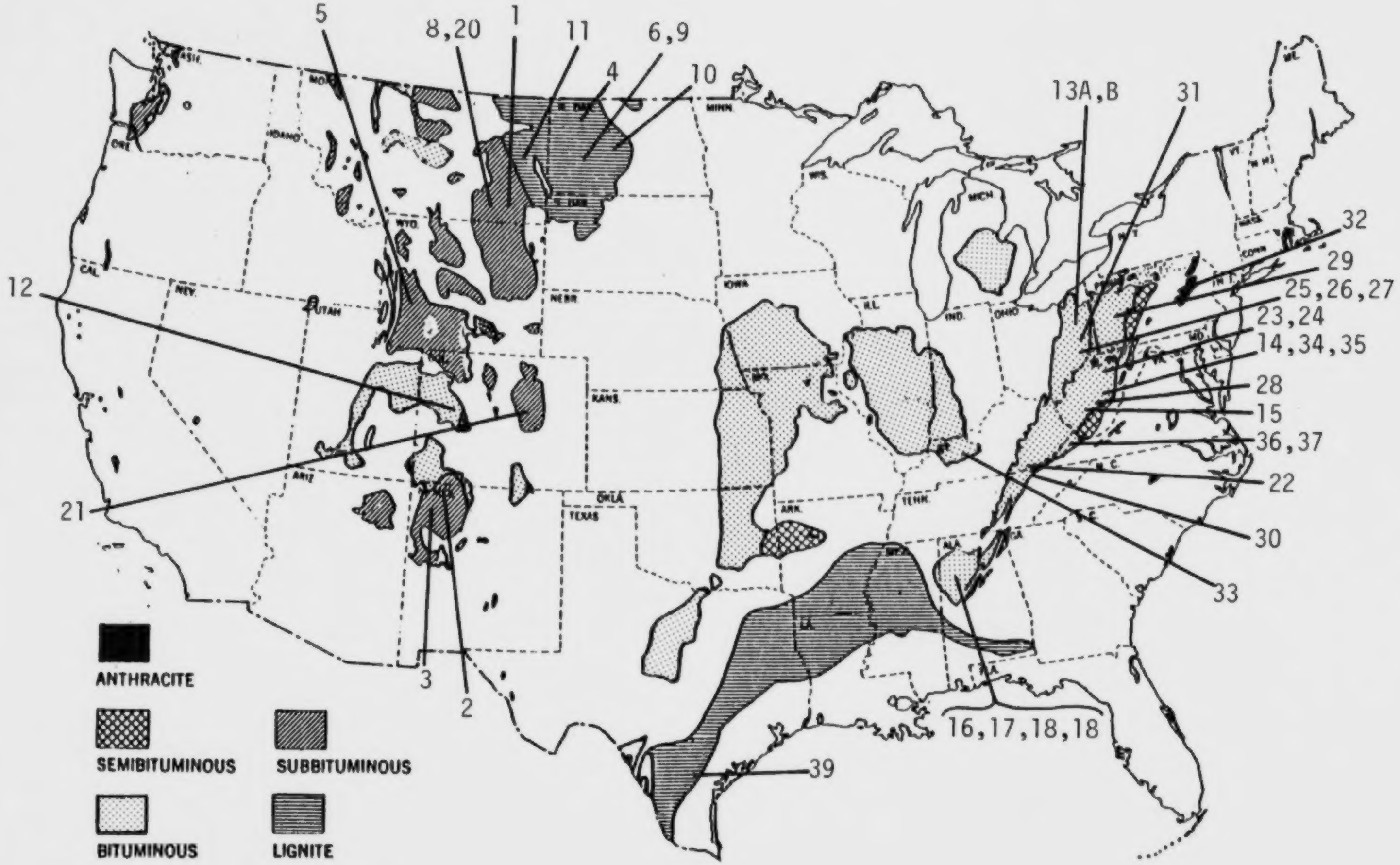

5
8,20
1
11
4
6,9
10
13A,B
31
32
29
25,26,27
23,24
14,34,35
28
15
36,37
22
30
33
12
21
3
2
16,17,18,18
39
ANTHRACITE
SEMIBITUMINOUS
SUBBITUMINOUS
BITUMINOUS
LIGNITE

Figure 2-3. Geographical Location of Coals Available for Testing at EER.

to be used throughout this contract. Three basic questions have been addressed:

- What information is required?
- What measurements will produce this information?
- How should these measurements be carried out?

There are three basic data groups associated with all of the experimental tasks included in this program. These are shown schematically in Figure 2-4 which also lists the information that must be obtained. The input parameters define the initial conditions and, therefore, represent the independent system variables. The in-flame and output information represent the dependent system variables. The effort necessary to obtain all the information shown in Figure 2-4 is very large and it is inappropriate to make all these measurements continually. The general approach is to gather a minimum of information when screening a large number of variables and as the number of variables is diminished, the number of measurements can be increased to accomplish all the objectives. In the end, it might be desirable to perform a complete series of EPA Level I analyses for a limited set of conditions.

2.2.1 Specification of Necessary Measurements

Figure 2-4 outlined the measurement requirements in the three general areas: input, in-flame and output. This section summarizes the measurements and frequency of the measurement to be conducted during this program. The measurements are labeled as "routine" when they are made at each stable operating condition and "non-routine" when they are made on an intermittent basis. The frequency of the non-routine measurements are defined by the specific experimental objectives.

Input Measurements

The information associated with the input conditions shown in Figure 2-4 are divided into two general classes: 1) Information defining the hardware of the burner and furnace, and 2) information regarding the characteristics of reactants. The hardware-oriented information is considered routine and includes:

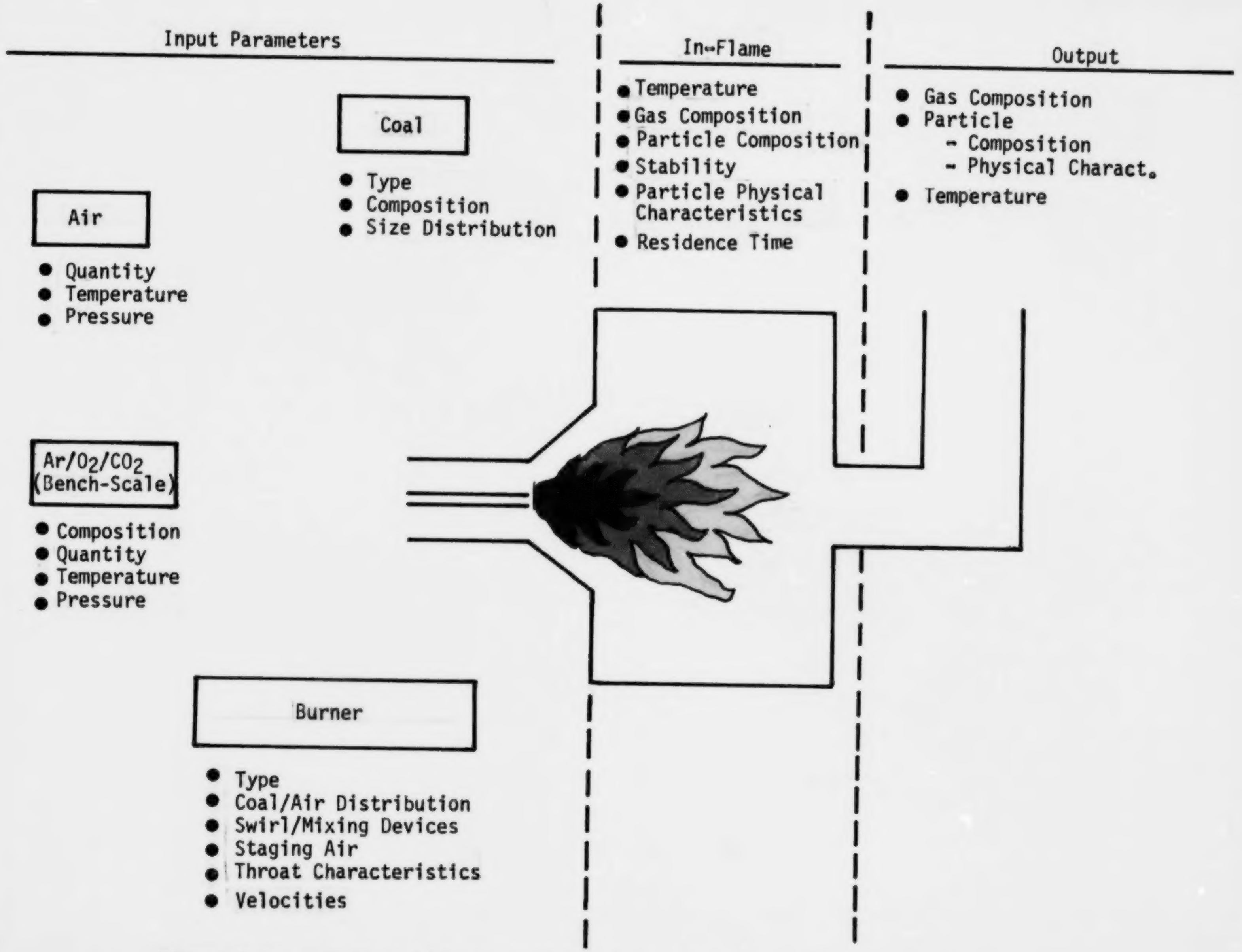

Input Parameters
In-Flame
Output
Air
• Quantity
• Temperature
• Pressure
Coal
• Type
• Composition
• Size Distribution
Ar/O_2/CO_2 (Bench-Scale)
• Composition
• Quantity
• Temperature
• Pressure
Burner
• Type
• Coal/Air Distribution
• Swirl/Mixing Devices
• Staging Air
• Throat Characteristics
• Velocities
• Temperature
• Gas Composition
• Particle Composition
• Stability
• Particle Physical Characteristics
• Residence Time
• Gas Composition
• Particle
- Composition
- Physical Charact.
• Temperature

Figure 2-4. Summary of Measurement Requirements on Experimental Furnaces.

- Physical description of the furnace (dimensions, volume, etc.).
- Burner description (type, exit dimensions, swirl parameters, diameter of channels, injection angles, etc.). These measurements and observations allow the dependent variables of the burner to be controlled (velocities turbulence, mixing, stoichiometries, etc.).
- Burner configuration, relationship to furnace, and a burner-to-burner spacing for multiple burners.

The reactants are composed of fuel (oil, gas, or coal), oxidant (oxygen) and diluents (nitrogen or argon and carbon dioxide). Coal is the fuel used in this program, and the required measurements are listed in Table 2-1. The frequency of routine analyses should be sufficient to define the characteristics of the input coal taking into account the requirements of the experiment. The non-routine analyses shown in Table 2-1 are performed only when the specific experimental objectives necessitate the need for this information. The uneven distribution of sulfur in coal makes it imperative that more frequent analysis of input coal be conducted. In this case, a slipstream from the coal feed line will be used from which samples are taken and analyzed for sulfur. In addition to information on fuel composition the coal feed rate must be known preferably by an independent method.

The other components of the reactants are the oxidant and the accompanying diluents. The most important measurement relates to the quantity of oxygen available for reaction. This requires a measurement of the airflow rate to the burner, or when an artificial oxidant mixture is used, the flow rate of the individual components. These are considered routine measurements that must be made on a continuous basis. Also, the temperature of the oxidant must be recorded continuously.

Table 2-1. Characterization of Coal

Routine
Coal Type Heating Value Proximate Analysis Ultimate Analysis
Non-Routine
Analysis of the Ash Sulfur Forms Analysis Trace Metal Analysis Physical Properties (eg. grindability, response to heating, hardness, etc.) Size Distribution Petrographic Analysis Functional Group Analysis

In-Flame Measurements

The entire group of in-flame measurements is non-routine and will be made intermittently during specific experiments. The temperatures of the gas and particles as well as the gas-phase composition are the main measurements of interest. Gas species to be measured are NO, NO_2, SO_2 and potential intermediates to these species such as NH_3, HCN, H_2S, CH_3, SH, etc.

There are several measurements on the solid phase that are required, such as:

- Char composition
- Char morphology
- Composition, surface area and morphology of sorbent particles

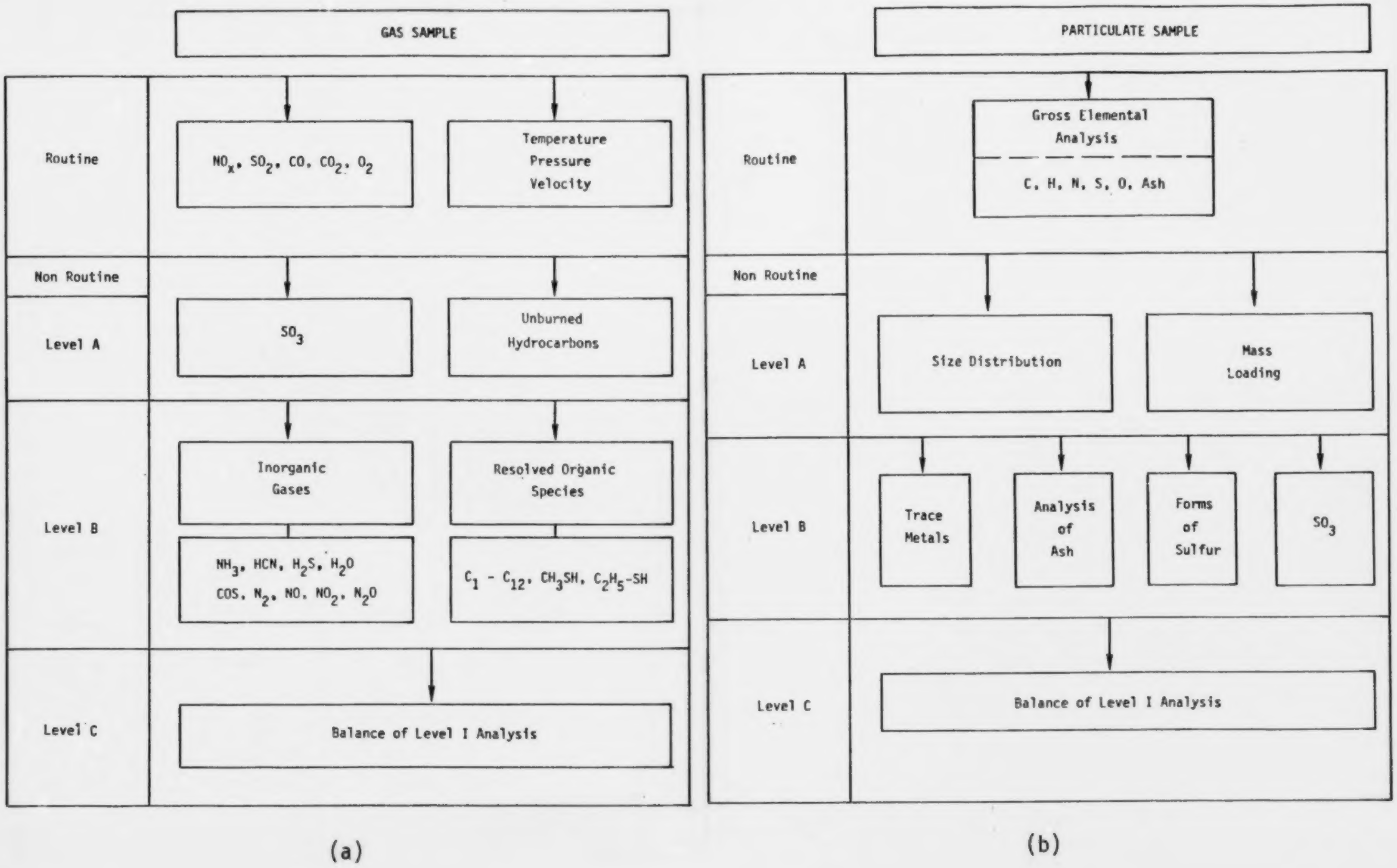
In addition to the non-routine measurements for the specific species described above, there are the gross physical observations that are made on a routine basis inside the furnace. Flame shape, stability and ignition distance are important parameters and are a directly related burner operation. These are qualitative visual observations in most cases, but nevertheless are recorded as an integral part of the data.

Output Measurements

The measurements made at the output of the furnace are the most important dependent variable of the system. A summary of the measurements applicable to the present program are listed in Figure 2-5, which shows that a phased approach in which the non-routine measurements will be performed in a manner to include a complete Level I Analysis. A scheme for the EPA Level I Analysis is outlined in Figure 2-6. Attempts will be made to collect samples on which the entire Level I Analysis will be performed.

2.2.2. Measurements Methods

In most cases, there are several methods or techniques that might be employed. There are advantages and disadvantages to each with respect to cost, ease of analysis, accuracy, precision and general compatibility with the facilities at Energy and Environmental Research Corp (EER).


GAS SAMPLE
Routine
Non Routine
Level A
Level B
Level C
NO$_x$, SO$_2$, CO, CO$_2$, O$_2$
Temperature
Pressure
Velocity
SO$_3$
Unburned
Hydrocarbons
Inorganic
Gases
NH$_3$, HCN, H$_2$S, H$_2$O
COS, N$_2$, NO, NO$_2$, N$_2$O
Resolved Organic
Species
C$_1$ - C$_{12}$, CH$_3$SH, C$_2$H$_5$-SH
Balance of Level I Analysis
(a)
PARTICULATE SAMPLE
Routine
Non Routine
Level A
Level B
Level C
Gross Elemental
Analysis
C, H, N, S, O, Ash
Size Distribution
Mass
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Trace
Metals
Analysis
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Ash
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of
Sulfur
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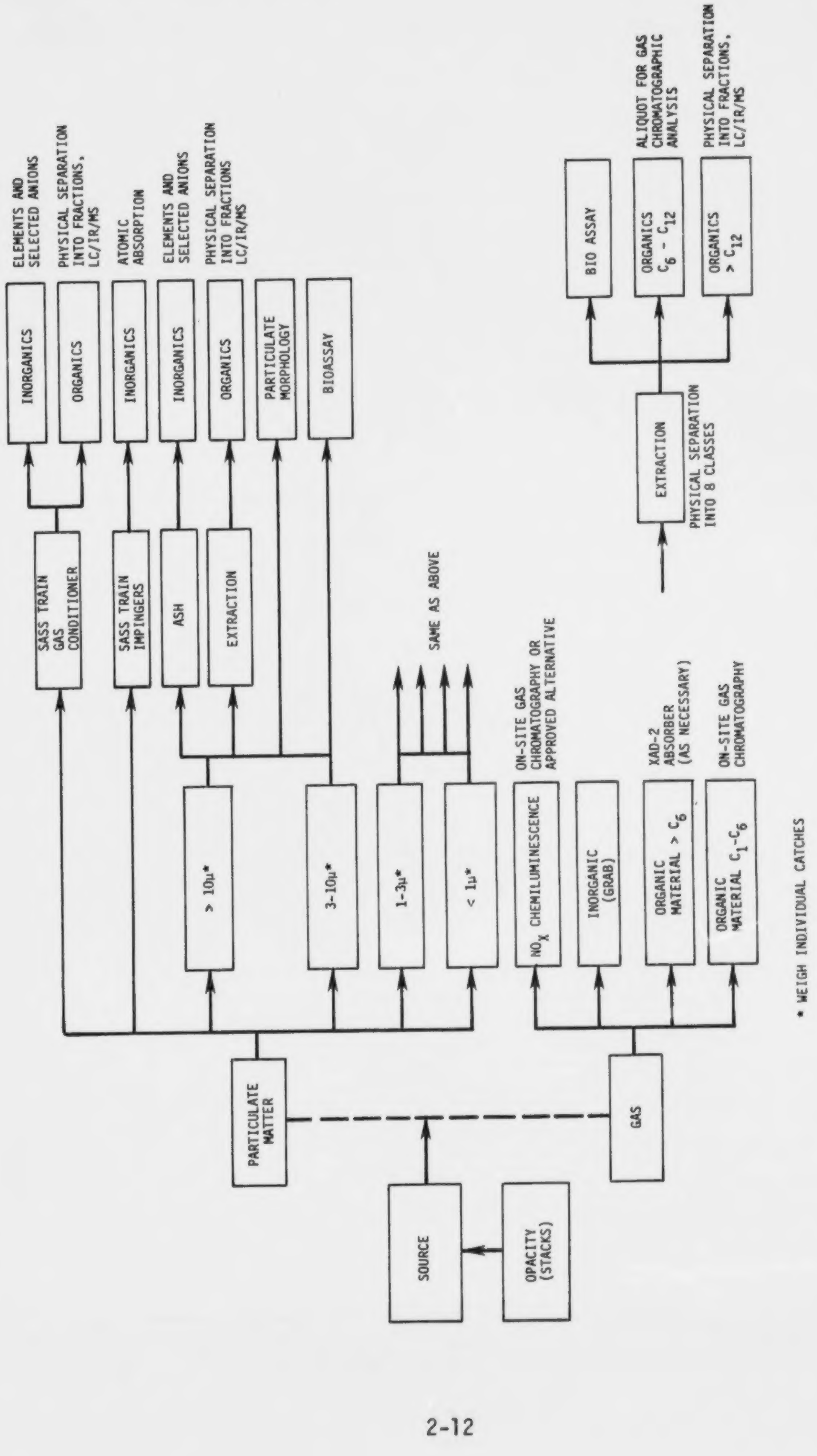
Balance of Level I Analysis
(b)

Figure 2-5. Phase Approach to Output Measurements.
a) Flue Gas, b) Particulate


SOURCE
OPACITY (STACKS)
PARTICULATE MATTER
GAS
SASS TRAIN GAS CONDITIONER
SASS TRAIN IMPINGERS
> 10μ*
3-10μ*
1-3μ*
< 1μ*
ASH
EXTRACTION
SAME AS ABOVE
INORGANICS
ELEMENTS AND SELECTED ANIONS
ORGANICS
PHYSICAL SEPARATION INTO FRACTIONS, LC/IR/MS
INORGANICS
ATOMIC ABSORPTION
INORGANICS
ELEMENTS AND SELECTED ANIONS
ORGANICS
PHYSICAL SEPARATION INTO FRACTIONS LC/IR/MS
PARTICULATE MORPHOLOGY
BIOASSAY
NO_X CHEMILUMINESCENCE
ON-SITE GAS CHROMATOGRAPHY OR APPROVED ALTERNATIVE
INORGANIC (GRAB)
ORGANIC MATERIAL $> C_6$
XAD-2 ABSORBER (AS NECESSARY)
ORGANIC MATERIAL C_1-C_6
ON-SITE GAS CHROMATOGRAPHY
EXTRACTION
PHYSICAL SEPARATION INTO 8 CLASSES
BIO ASSAY
ORGANICS C_6 - C_{12}
ALIQUOT FOR GAS CHROMATOGRAPHIC ANALYSIS
ORGANICS $> C_{12}$
PHYSICAL SEPARATION INTO FRACTIONS, LC/IR/MS

* WEIGH INDIVIDUAL CATCHES

Figure 2-6. Basic Level 1 Sampling and Analytical Scheme for Particulates and Gases.

Coal Analysis

The sampling and analysis of the coal will proceed basically according to the ASTM procedures. Exception to these established methods will be accompanied with data to demonstrate that comparable values can be achieved with the other method. Examples of this are the use of an elemental analyzer to perform the analysis of carbon, hydrogen, nitrogen and ash and an x-ray fluorescence instrument for sulfur and mineral compounds. As these instruments are integrated into the EER measurements system, suitable comparison will be made.

Measurement of the coal feed rate has proven to be very difficult and it has been concluded that a gravimetric measure of the crushed coal into the pulverizer is the best alternative available, and the LWS and LWS systems will be upgraded to include such a device. The firing rate in a furnace will also be determined from the measured airflow rates coupled with the exhaust O_2 as a check upon the measured feed rate.

Gas-Flow Measurement

A knowledge of the input gas flow rate is necessary for all of the experimental tasks. Venturi meters of the Herschel type are used widely and are easily incorporated into the continuous measurement system at EER. The pressure drop across them is low and they provide an accurate measure in the flow ranges used. Rotometers are used for the smaller flows on the bench-scale furnaces and orifices are utilized when appropriate.

Output Species

Continuous analyses are available for all the routine gas analyses specified above and their accuracy is usually comparable or even superior to the techniques prescribed by the EPA methods. The preferred methods for these and other potential measurements are listed in Table 2-2. Since most of the experimentation conducted at EER is or will be related to field data where compliance measurements are collected, the EPA methods have been incorporated as quality control checks. Periodically, comparable samples will be collected for analysis by both the EPA method and the method indicated in Table 2-2.

Table 2-2. Summary of Methods for Output Measurement

Routine Measurements	Frequency*	Test Methods	QC Checks	QC Double Checks
NO	C	Chemiluminescent	Calibration Gases Method 7	
NO_2	I	Chemiluminescent	Method 7	Compare With Data Taken From Other Instruments
NO_x	I	Chemiluminescent	Method 7	
CO	C	NDIR	Method 3	
CO_2	C	NDIR	Method 3	
Total UHC	C	FID		
O_2	C	Paramagnetic	Method 3	
SO_2	C	UV Absorption	Method 6	
SO_3	I	Shell Method in Triplicate	Method 8	
Particulate Mass	I	Method 5	Triplicate Samples Anderson Impactor	Compare With Outside Organization
Particulate Size	I	Using SASS Train		
Opacity	I	Method 9	Triplicate Measurements	

Non-Routine	
Condensable Gas Mass/Composition	SASS/Level I
Particulate Composition	SASS/Level I
Elemental	SASS/Level I
SO_4, NO_3, CO_3	SASS/Level I
C, H, N, S	SASS/Elemental Analyzer
Organics	SASS/Level I
Organic Species	SASS/Level I

*C = Continuous
I = Intermitent

In Flame Measurements

The measurement of conditions within or close to the heat release zone in a combustion system (in flame) introduces problems associated with sample acquisition and analysis. In some instances the method of acquisition influences the analysis method. Table 2-3 lists the advantages and disadvantages associated with various probe types and Table 2-4 compares the analysis techniques for water and non-water quench probes. The use of a water quench complicates the analysis but its use is preferred because of the capability to rapidly quench both gases and solids. Water quench probes are used in both the bench and pilot scale experiments. Although gas temperatures are measured most easily by thermocouples it should be remembered that they only indicate their own temperature which may not be the same as the gas in which they are immersed. Thus for conditions where the thermocouple can have significant radiative interchange shielded thermocouples are necessary. Suction pyrometers are used for in flame measurements to give a measurement of gas temperature.

Table 2-3. Probes Used for Sampling Inside a Coal Flame

Probe	Advantages	Disadvantages
Stainless Steel, Water-cooled	1. Easy conveyance of sample 2. Simple construction 3. Widely used	1. Cool radiative surface in flame 2. Plugs easily 3. Reactive surface for hot gases
Stainless Steel, Water-Quench	1. High quenching rate 2. Minimum of secondary reaction with walls 3. Removes particulates 4. Minimizes plugging due to solids	1. Complex construction 2. Secondary reactions with water and hot gases 3. Partial solubility of gases and particles in water 4. Requires separation of liquids and gases
Uncooled Quartz	1. Relatively inert surface 2. Can withstand temperatures up to ∿900°C 3. Slow quenching 4. Simple construction	1. Devitrification occurs @ temp's above 900-1000°C 2. Plugging problems 3. Interface problems with furnace and sample lines 4. Fragile
Cooled Quartz (air, steam, or H_2O)	1. Inert, cool surface	1. Fragile, difficult construction 2. Plugging problems 3. Interface problems
Sonic Cooled Quartz/Stainless Steel	1. Inert, cool surface	1. Small orifice, plugging problems 2. Fragile and interface problems

Table 2-4. Summary of Methods for Use with Different Sample Systems

	Method		
	Water Injection		Non-Water Injection
	Liquid	Gas	
NH_3	S.I.E.*	-	Gas Chromatograph
HCN	S.I.E.*	-	Gas Chromatograph
H_2S	S.I.E.*	-	Gas Chromatograph
SO_2	Partial Sulubility	-	UV Absorption
NO_x	-	Chemiluminscent	Chemiluminescent
CO_2	-	NDIR	NDIR
CO	-	NDIR	NDIR
O_2	-	Paramagnetic	Paramagnetic
Particles+			

* - Selective Ion Electrode

+ - Particles must be separated from liquid with some potential loss of certain components.

3.0 BENCH-SCALE STUDIES — COAL PROPERTIES AND NITROGEN OXIDE FORMATION

In the first year's effort a bench-scale reactor was constructed which has a design input firing rate ranging from 50 x 10^3 Btu/hr to 150 x 10^3 Btu/hr. This facility was to be used for fuel screening studies and concept development. This bench-scale facility was built with several versatile features including:

- The ability to burn the fuel with nitrogen-free oxidant mixtures composed of O_2, CO_2 and argon in order to define fuel NO production.
- Complete control over fuel input rate and fuel size distribution.
- Modular combustion chamber construction to allow for probe access and the opportunity for variable heat extraction rates.

Twenty-five coals have been tested to date in this furnace, and this section presents the results from the Task 2 studies. In the first section the impact of fuel properties on NO formation under excess air and simple staged conditions is discussed. The second section presents the data obtained to date on an evaluation of advanced concepts for NO_x control.

3.1 The Influence of Coal Properties on NO Formation

Figure 3-1 presents data obtained from a series of EPA-sponsored field tests on the emission of NO_x from various pulverized coal boiler designs. The data refers to bituminous coal, and emissions are presented as a function of percentage nitrogen on a dry ash-free basis (DAF). The symbols differentiate between firing method and uncontrolled conditions. In general, wall-fired units have emissions which exceed those from corner-fired units under uncontrolled conditions. Under controlled conditions emissions from both wall-fired and corner-fired units are similar. From the data presented it appears that turbo units have characteristics which produce emission levels that vary considerably from unit to unit. The data from the one arch-fired unit presented shows NO levels under uncontrolled conditions which are relatively low. From the data presented in Figure 3-1 it appears that there

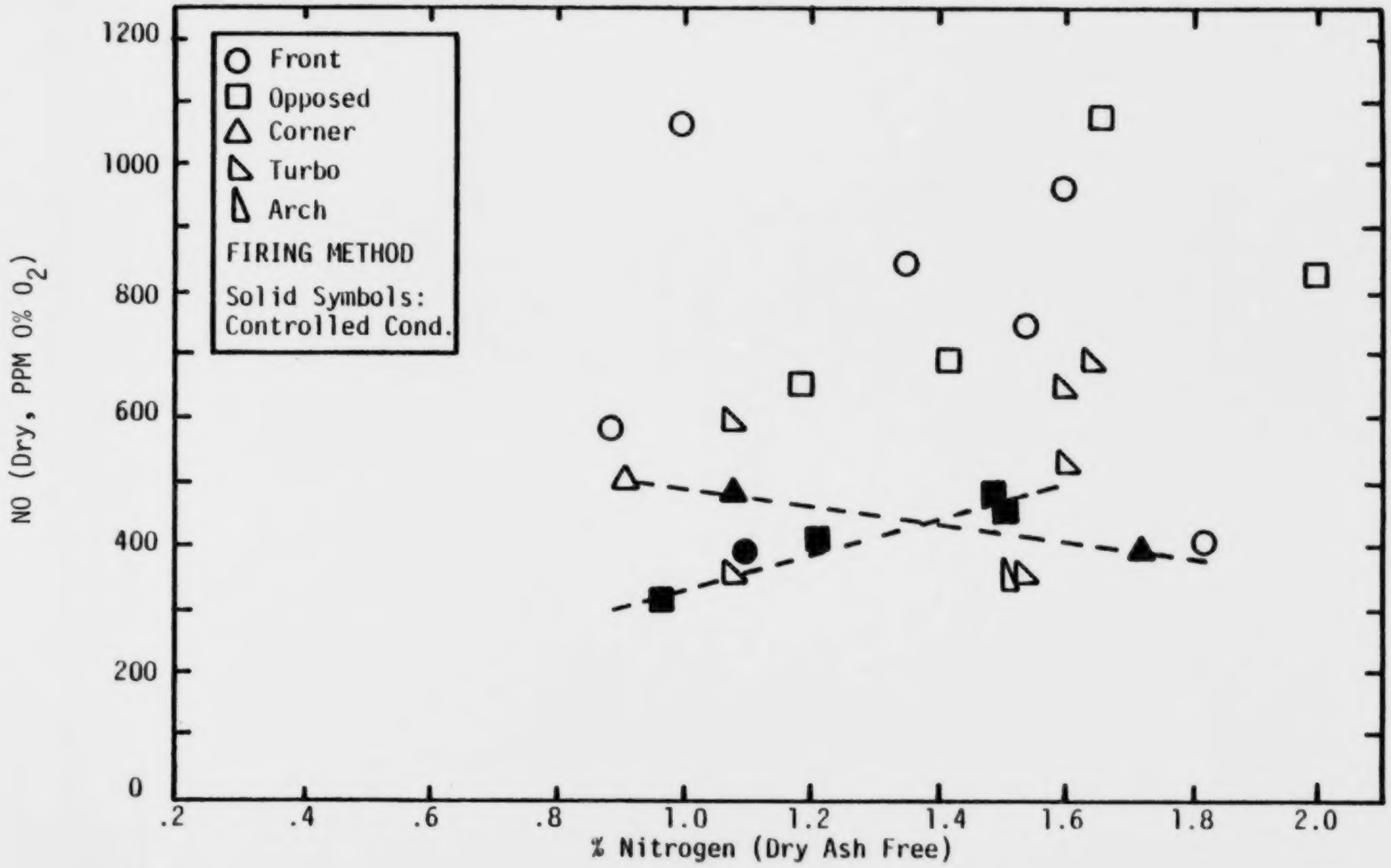


Figure 3-1. Fuel Properties and Firing Method Impact NO_x Emissions from Boiler.

is no systematic change in emission level with coal nitrogen compounds, although under low NO_x conditions there is a suggestion that emissions increase with increasing nitrogen content for wall-fired units and decrease for corner-fired units. The bench-scale studies were planned to try and isolate the influence of coal properties and firing method in order to provide information which allows the generalization of low NO_x combustor technology to a wide range of fuels.

The nitrogen in coal is bound in the organic matrix and is released during thermal decomposition either as a light gas, or bound in a similar fashion to the original coal in some high molecular weight hydrocarbon gas. The fraction of nitrogen released during thermal decomposition is most strongly dependent upon the final particle temperature, and the time at that temperature. Essentially, all nitrogen can be released from the char if it is maintained long enough at a high enough temperature. Thus, fuel NO can be formed either by oxidation of the nitrogen that remains with the char, or from the volatile fuel nitrogen compounds. In this instance volatiles refers to the products of thermal decomposition which may undergo secondary pyrolysis producing HCN, even though HCN is not a primary decomposition product. Secondary pryolysis might well produce some solid which also contains nitrogen. The factors determining the fate of the volatile fuel nitrogen are relatively well-understood. If oxygen is available and mixed with the volatile nitrogen specie, then the formation of NO is favored. However, under fuel-rich conditions the XN specie tend to form N_2. The fate of the nitrogen remaining in the solid (char nitrogen) is less well-understood. Several experiments have been carried out which suggest that char nitrogen conversion to NO is low, although it is quite probable that the nitrogen is actually released from the char as NO. This NO will probably form N_2 as it diffuses through the pores and away from the char particle. The experiments carried out to date make no attempt to differentiate between the nitrogen which is evolved from the coal as a gas or tar during thermal decompsition, or remains with the char.

It is reasonable to assume that char nitrogen conversion is relatively low, and that therefore the two factors which will determine the conversion of fuel nitrogen to NO will be the fraction of the total nitrogen evolved with the volatiles and some parameter related to mixing of the fuel and the oxidant. Mixing will be determined by the fuel/air contacting process, and the volatile nitrogen evolution will be dependent upon both the coal type and the environment in which the coal finds itself, since volatile nitrogen evolution is largely temperature-dependent.

3.1.1 The Influence of Fuel/Air Contacting

Pulverized coal is burned in diffusion flames; i.e., the fuel and air are not mixed before injection into the furnace and mixing and heat release take place concurrently. In wall-fired units the fuel/air mixing occurs very close to the point of fuel injection, giving a relatively rapidly mixed system stabilized at the burner because of the formation of an internal recirculation zone. In a corner-fired unit the fuel is injected axially from a series of ports at the four corners of the boiler. These injectors are directed on a tangent to a firing circle. The flame can be likened to a long turbulent diffusion flame which coalesces into a ball in the center of the furnace. A small-scale swirl burner was used in the bench-scale experiments with an interchangeable fuel injector to provide conditions which resemble those encountered in these two boiler types. When the coal was injected radially into a relatively high swirling flow the backmixed swirling diffusion flame has similar characteristics to those encountered in wall-fired boilers. The fuel/air mixing characteristics of a corner-fired unit were approximated by using a single axial fuel injector and the addition of only sufficient swirl on the combustion air to provide a stable ignition zone close to the fuel injector which gave a slow mixing diffusion flame. A third system was used to provide an upper limit for fuel/air mixing. This involved totally premixing the coal and transport air before it was injected into the furnace. The coal then burns as a plug flow suspension. Figure 3-2 shows a sketch of the three burner systems which will be referred to as premixed, radial diffusion, and axial diffusion.

All the coals investigated were ground to provide more than 65 percent of their weight less than 70 microns. They were then burned with air and with argon/CO_2/oxygen mixtures in the three different burner systems. Figure 3-3 presents typical data for one fuel, a Utah bituminous coal. NO corrected to 0 percent oxygen is shown as a function of excess oxygen.

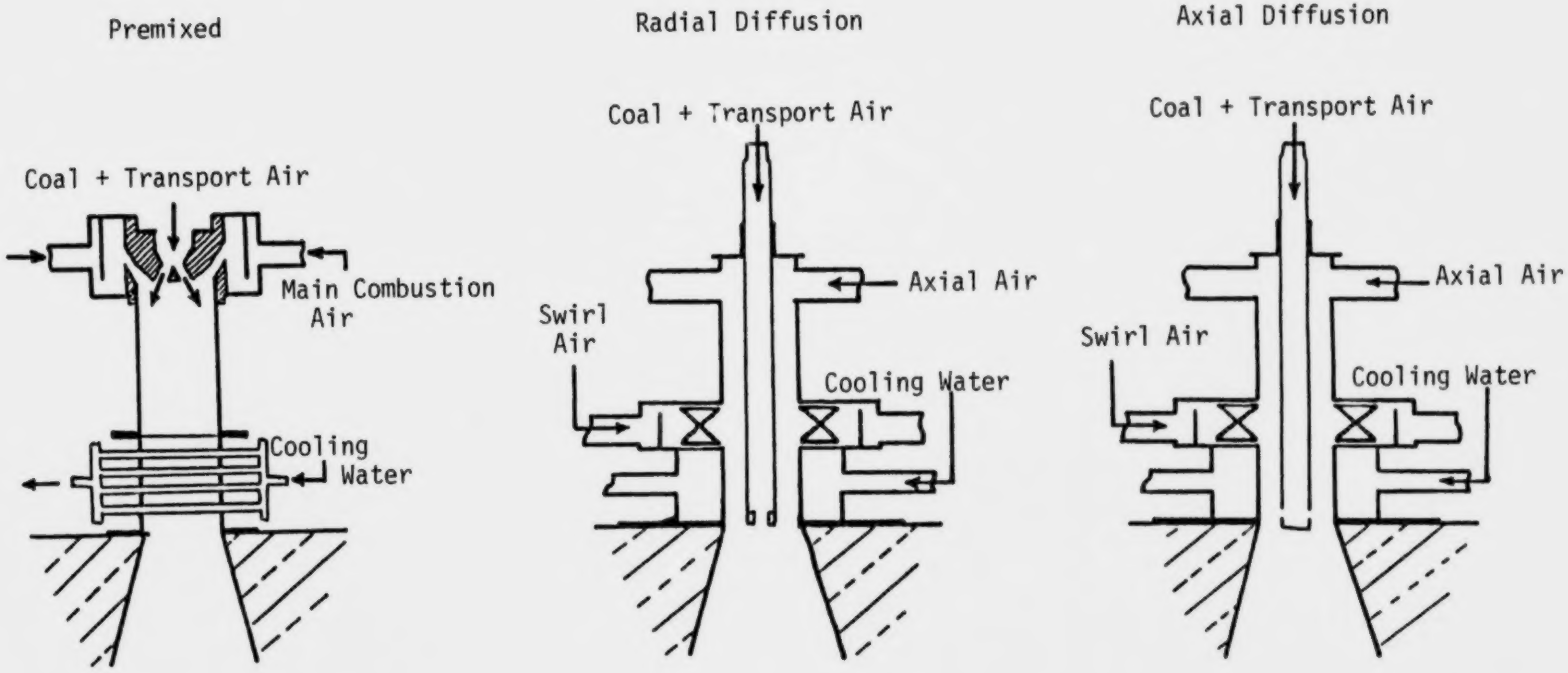

Premixed
Radial Diffusion
Axial Diffusion
Coal + Transport Air
Main Combustion Air
Cooling Water
Coal + Transport Air
Swirl Air
Axial Air
Cooling Water
Coal + Transport Air
Swirl Air
Axial Air
Cooling Water

Figure 3-2. Different Burners Used on the Bench-Scale Furnace.

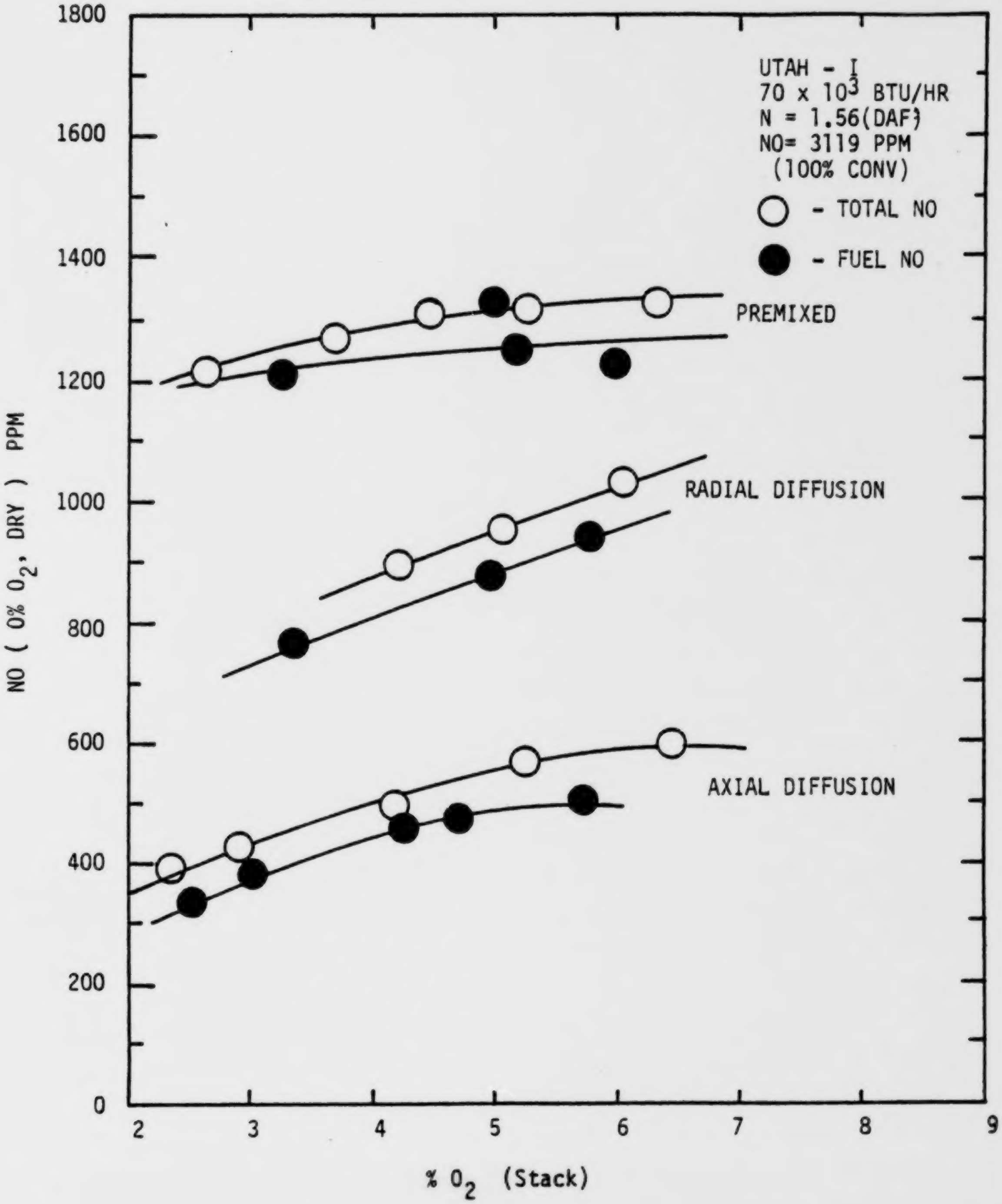


Figure 3-3. Summary of NO Emission of Excess Air Conditions for Baseline Utah Bituminous Coal in Small-Scale Furnace.

Total NO refers to measurements made with air as the oxidant, and fuel NO is obtained with the artificial oxidant mixtures. Table 3-1 presents the characteristics of the coals tested to date. These include: one anthracite, 14 bituminous, three subbituminous, six lignites, and one char obtained from a bituminous coal. The results from all the coals tested to date are presented in Appendix B.

The data obtained under excess air conditions is summarized in Figures 3-4, -5, and -6 for the premixed, radial diffusion and axial diffusion flame burners, respectively. Fuel NO emissions are shown in parts per million and pounds of NO_2 per 10^6 Btu as a function of percentage nitrogen in the coal on a dry ash-free basis for overall 5 percent excess oxygen in the combustion products. The data as presented illustrate two major points:

1. Fuel NO emissions tend to increase with increasing fuel nitrogen content. This is most pronounced for the premixed, and radial diffusion flames. However, for any given nitrogen content there is a considerable spread in fuel NO emissions, indicating that some property other than total fuel nitrogen content influences fuel NO formation.
2. Fuel nitrogen conversion decreases with decreasing fuel/air mixing rates. Since oxygen availability controls fuel NO formation, this is to be expected.

The examples presented in Figures 3-4, 3-5 and 3-6 show some of the anomalous behavior associated with fuel/air mixing effects and fuel nitrogen formation. Some coals show a very strong dependence of fuel nitrogen formation on fuel/air mixing characteristics. However, this is not always the case, and even for coals of the same rank it appears that the influence of fuel/air mixing is also coal-dependent. Two fuels tested to date show very different characteristics. The anthracite shows almost no impact of fuel/air mixing rate. Since anthracite is very low in volatile content, it can be assumed that the major portion of the fuel NO formed is produced from solid nitrogen, and that the impact of fuel/air mixing characteristics would be minimized. Alternatively, the Australian lignite showed a decrease in fuel NO from 950 to 675 to 175 PPM as the

Table 3-1. Fuel Analysis

Fuel Symbol	D	✜	∩	⬡	◇	⌂	♢	⬭	○	◺	⊘	⊗	▢
Fuel Source	Hazelton PA.	Upper Cliff Alabama	Rosa Alabama	Black Creek Alabama	W. KY.	W. VA.	Elkay W. VA.	Gauley Eagle W. VA.	Price Utah I	Price Utah II	Utah (Coal)	Utah (Char)	Cadiz Ohio
Proximate Analysis (% as received)													
Moisture	5.13	3.00	8.02	2.25	5.43	7.57	0.60	3.72	6.39	7.41	4.20	2.70	4.29
Ash	5.74	9.49	6.79	4.45	7.53	12.05	11.61	26.89	7.40	8.83	9.62	16.83	18.05
Volatile Matter	4.39	20.44	21.81	28.28	37.79	29.12	33.35	26.65	38.89	38.84	42.97	10.29	34.87
Fixed Carbon	84.74	67.07	63.38	65.02	49.25	51.26	54.44	42.74	47.32	44.92	43.21	70.18	42.79
Ultimate Analysis (% Dry)													
C	88.45	79.32	81.23	82.12	71.58	74.68	73.96	59.43	73.52	72.24	69.36	75.39	62.08
H	2.14	4.47	4.73	5.21	5.43	4.96	4.93	4.11	5.52	5.75	5.32	1.28	4.44
N	0.79	1.47	1.54	1.79	1.55	1.38	1.39	1.35	1.44	1.55	1.50	1.22	1.07
S	0.47	1.30	1.04	0.76	3.21	0.86	2.47	0.84	0.61	0.76	1.04	1.12	7.40
Ash	6.05	9.78	7.38	4.56	7.96	13.04	11.69	27.94	7.89	9.54	10.05	17.30	18.86
O	2.10	3.66	4.08	5.56	10.27	5.08	5.56	6.33	11.29	10.16	12.73	3.69	6.15
Heating Value (Btu/lb. Wet)	13,124	13,254	13,394	14,284	12,082	12,228	13,115	10,110	12,340	11,877	11,718	11,185	11,038
CLASSIFICATION (ASTM D388)	Anthracite	Medium Volatile Bituminous	Medium Volatile Bituminous	Medium Volatile Bituminous	High Volatile A Bituminous	High Volatile A Bituminous	High Volatile A Bituminous	High Volatile A Bituminous	High Volatile B Bituminous	High Volatile B Bituminous	High Volatile B Bituminous		High Volatile B Bituminous

Table 3-1. Fuel Analysis (cont.)

Fuel Symbol	◸	⦶	⬡	▽	⬯	◁	⬚	◇	⬡	□	△	◤	●
Fuel Source	Farmington N. M.	Four Corners N. M.	Fruitland N. M.	Colstrip Montana	Hardin Montana	Hardin Montana	Shell Texas	Scranton N. D.	Beulah N. D.	Beulah N. D.	Savage Montana	Morwell Australia	Saar Germany*
Proximate Analysis (% as received)													
Moisture	7.76	5.24	11.02	21.27	22.70	20.49	25.23	34.96	33.10	34.63	36.36	9.07*	2.16
Ash	17.96	24.06	20.72	9.58	11.26	8.62	10.28	7.50	7.12	4.97	4.61	3.38	8.04
Volatile Matter	34.95	35.94	31.66	30.82	31.26	33.24	35.31	28.85	28.65	27.02	28.48	48.79	36.23
Fixed Carbon	39.33	34.76	36.60	38.33	34.88	37.65	29.18	28.69	31.13	33.38	30.55	38.76	53.57
Ultimate Analysis (% Dry)													
C	63.06	55.99	58.71	67.52	65.54	67.88	60.99	64.61	65.29	66.15	64.99	66.25	76.13
H	4.65	4.71	4.21	4.36	4.15	4.65	4.49	4.17	3.96	4.20	4.04	5.01	5.25
N	1.40	1.23	1.30	1.38	0.95	0.99	1.13	0.83	0.99	0.96	1.00	0.65	1.37
S	0.81	1.03	0.93	0.63	0.79	1.07	1.02	1.52	1.14	0.37	0.42	0.28	0.83
Ash	19.47	25.39	23.29	12.17	14.57	10.84	13.74	11.53	10.64	7.60	7.25	3.72	8.21
O	10.61	11.65	11.56	13.94	14.00	14.57	18.63	17.34	17.98	20.72	22.30	24.09	8.21
Heating Value (Btu/lb, Wet)	10,391	9,425	9,344	9,169	8,603	9,229	8,131	6,446	7,245	7,254	6,995	10,051 (wet)	13,657 (dry)
CLASSIFICATION (ASTM D388)	High Volatile C Bituminous	High Volatile C Bituminous	High Volatile C Bituminous	Sub-Bituminous B	Sub-Bituminous B	Sub-Bituminous B	Sub-Bituminous C	Lignite A	Lignite A	Lignite A	Lignite A		

0 - Improve Definition

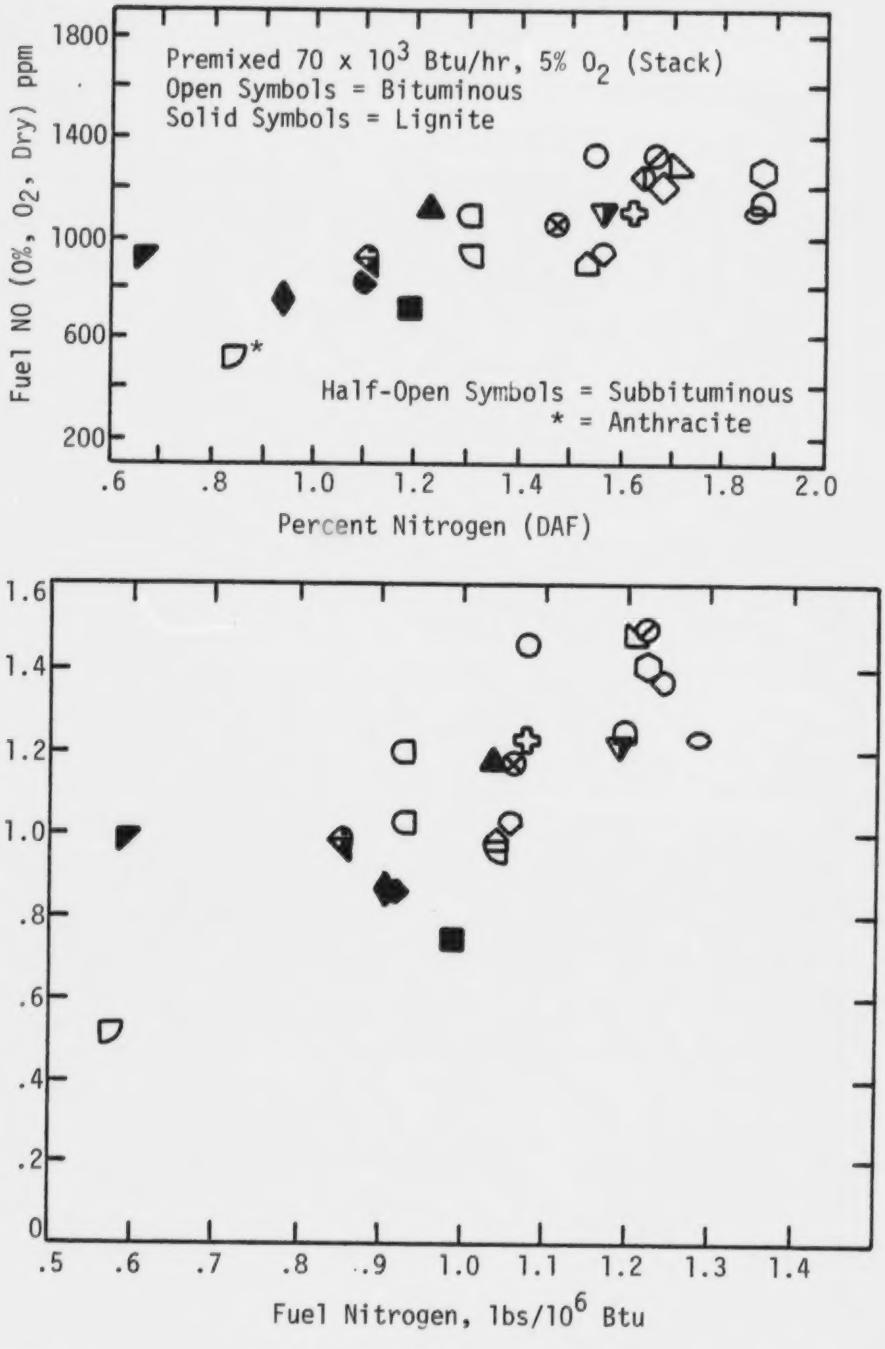
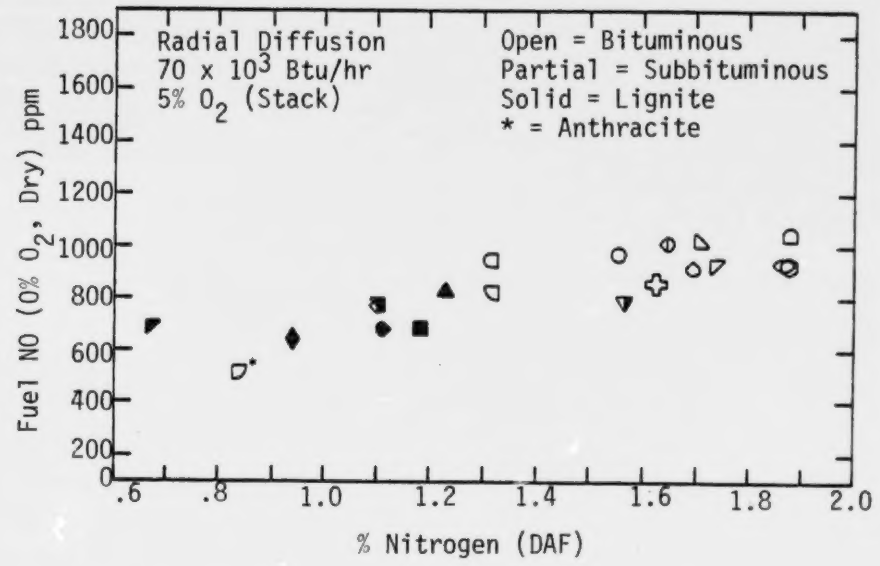


Figure 3-4. Summary of Fuel NO Emission for All Coals Tested with Premixed Burner in Argon Furnace.



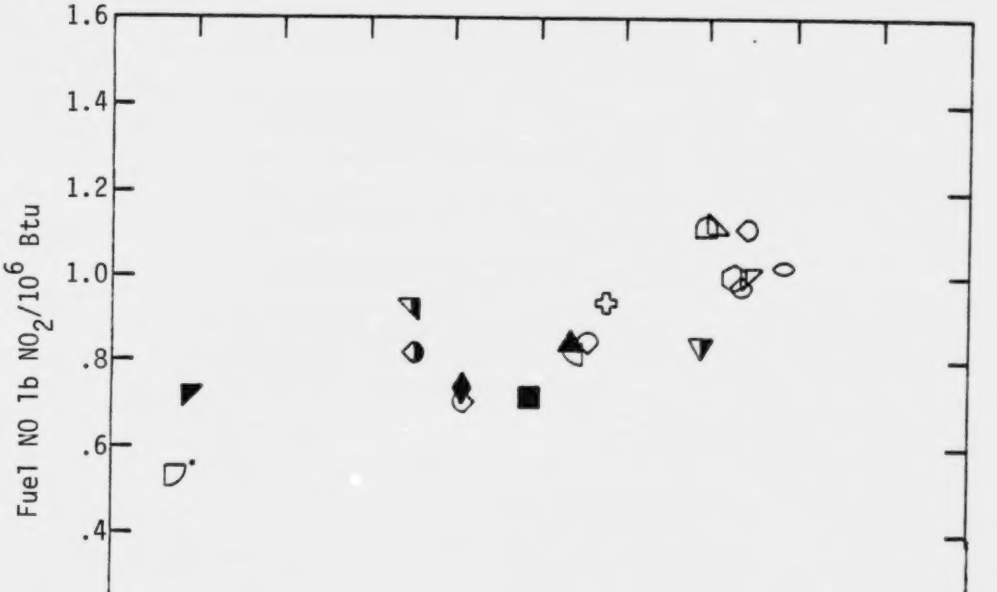
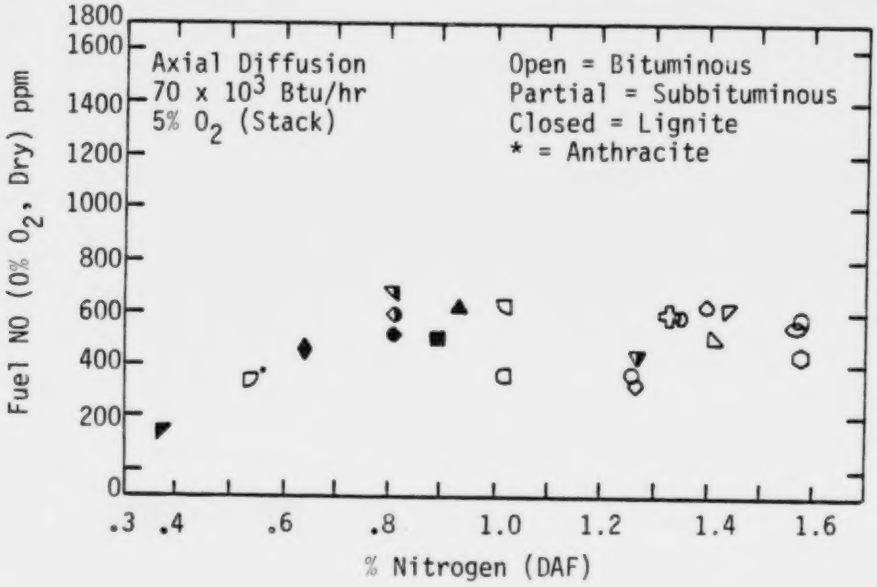


Figure 3-5. Summary of Fuel NO Emission for all Coals Tested with Radial Diffusion Burner in Argon Furnace.



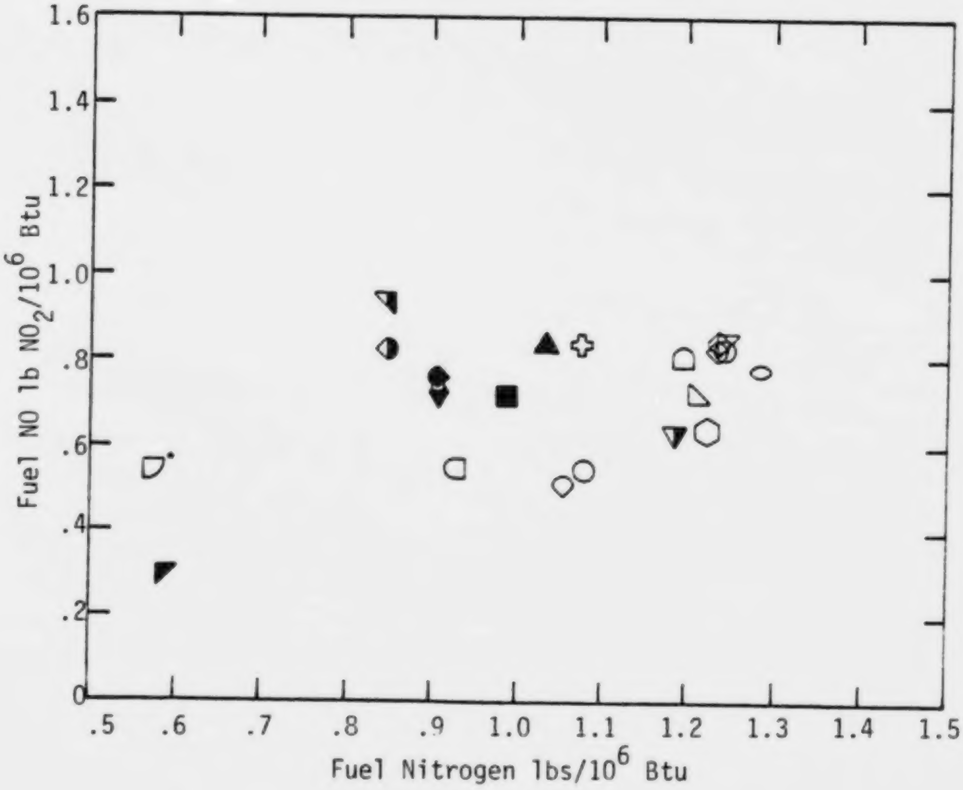


Figure 3-6. Summary of Fuel NO Emission for all Coals Tested to Date with Axial Diffusion Burner in Argon Furnace.

combustion conditions change from premix through radial diffusion to axial diffusion. This Australian lignite was predried, and therefore, has a very high volatile content and is extremely reactive.

3.1.2 The Influence of Thermal Environment

If the formation of fuel NO under excess air conditions is dependent upon the availability of volatile fuel nitrogen compounds, then increasing the particle temperature should increase fuel NO formation since it will increase the fraction of volatile fuel nitrogen compounds. In these experiments the thermal environment could be varied by varying the composition of the artificial oxidant mixture. For the results presented in Figures 3-3 through 3-6, carbon dioxide was added to the oxygen/argon mixture to provide a theoretical flame temperature which was the same as that for air fuel combustion. For a given oxygen concentration it was, therefore, possible to vary the thermal environment of the particles by varying the concentration of the carbon dioxide ballast. Earlier studies by Pershing et al. with axial diffusion flames indicated that the impact of the thermal environment of the particles as minimal. Current studies have confirmed that this is indeed the case for axial diffusion flames (see Figure 3-7). However, under premixed conditions fuel NO formation is very strongly dependent upon the thermal environment. The data presented in Figure 3-8 shows fuel NO as a function of calculated adiabatic flame temperature for premixed flames with various coals. Under premixed conditions fuel NO formation increases significantly with increasing adiabatic fuel temperature, although the rate of increase is apparently fuel-dependent.

The insensitivity of fuel NO formation from pulverized coal when it is burned in an axial diffusion flame to the calculated adiabatic flame temperature can be attributed to the fact that under these conditions any increase in volatile fuel nitrogen formation in the early stages of heat release will not influence exhaust NO values because oxygen is not available to form NO within the core of the diffusion flame.

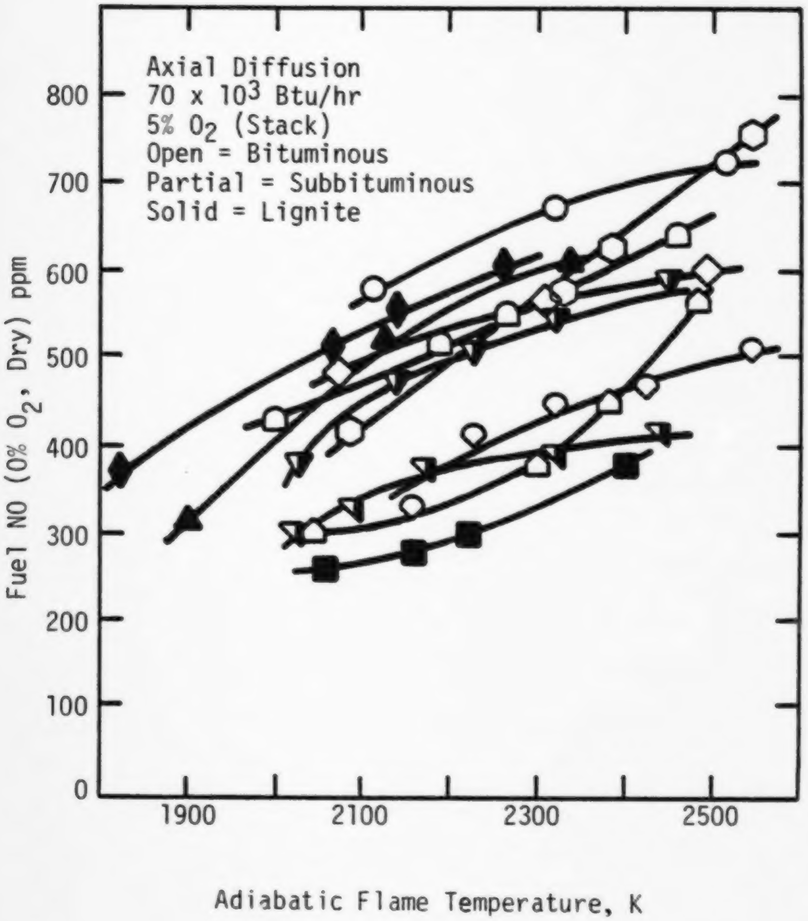


Figure 3-7. Fuel NO Formation Insensitive to Thermal Environment with Axial Diffusion Flame.

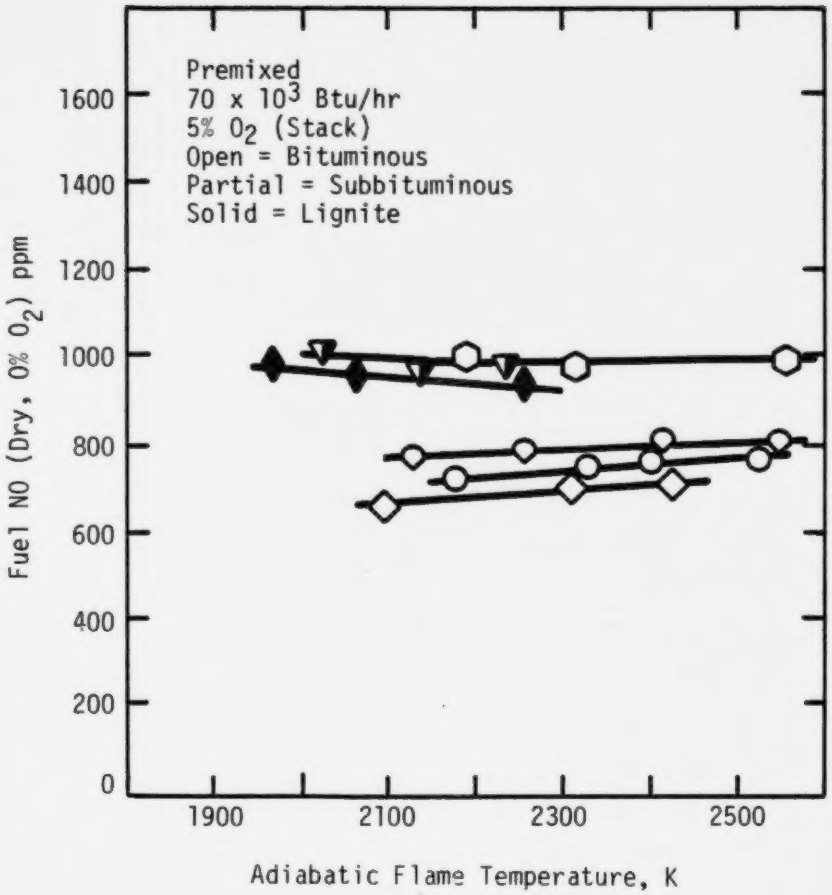


Figure 3-8. Thermal Environment Influence Fuel NO Formation Under Premixed Conditions.

3.1.3 The Effect of Staged Combustion

The formation of fuel NO can be minimized by operating the heat release zone deficient in oxygen. In this way the volatile fuel nitrogen compounds are more readily converted to N_2. A series of experiments were carried out to assess the impact of coal properties on NO formation under staged combustion conditions. For these experiments, air was used as the oxidant because questions concerning the chemical effect of argon substitution as a method of determining fuel NO production under fuel-rich conditions had arisen. Coal was transported by approximately 15 percent of the stoichiometric air requirement, and the first-stage air was varied to achieve the desired SR_1. Second-stage air was added downstream to ensure burnout, giving a constant overall excess oxygen of 5% in the exhaust. Figure 3-9 shows exhaust NO concentration as a function of primary zone stoichiometric ratio (SR_1) for a Utah bituminous coal using three burner configurations. It can be seen that as the stoichiometric ratio of the primary zone is reduced, the NO decreases, reaches a minimum and then increases. This minimum value is most pronounced with the premixed and radial diffusion flame burners. Also, the minimum level is influenced by the method of fuel/air contacting in the primary section. Data for all the coals tested is presented in Appendix C.

The impact of initial fuel/air contacting conditions shown in Figure 3-9 may be due to a combination of circumstances. For instance, the mean residence time will probably be influenced by the backmixed condition in the radial diffusion flame. It was also found that flame stability with the axial diffusion flame under staged conditions, was unsatisfactory for some coals, and therefore, the majority of the staged combustion experiments were carried out with the premixed and the radial diffusion flames. Minimum NO_x emissions achieved with these burners are presented in Figure 3-10 as a function of fuel nitrogen content. Emissions are largely independent of total fuel nitrogen content. The impact of fuel properties appears to be much more significant with the premixed system than with the radial diffusion flame. It should be noted that the results shown in Figure 3-10 do not represent the only impact of fuel properties, since they present only the minimum emission value and not the stoichiometric ratio at which that minimum value was achieved.

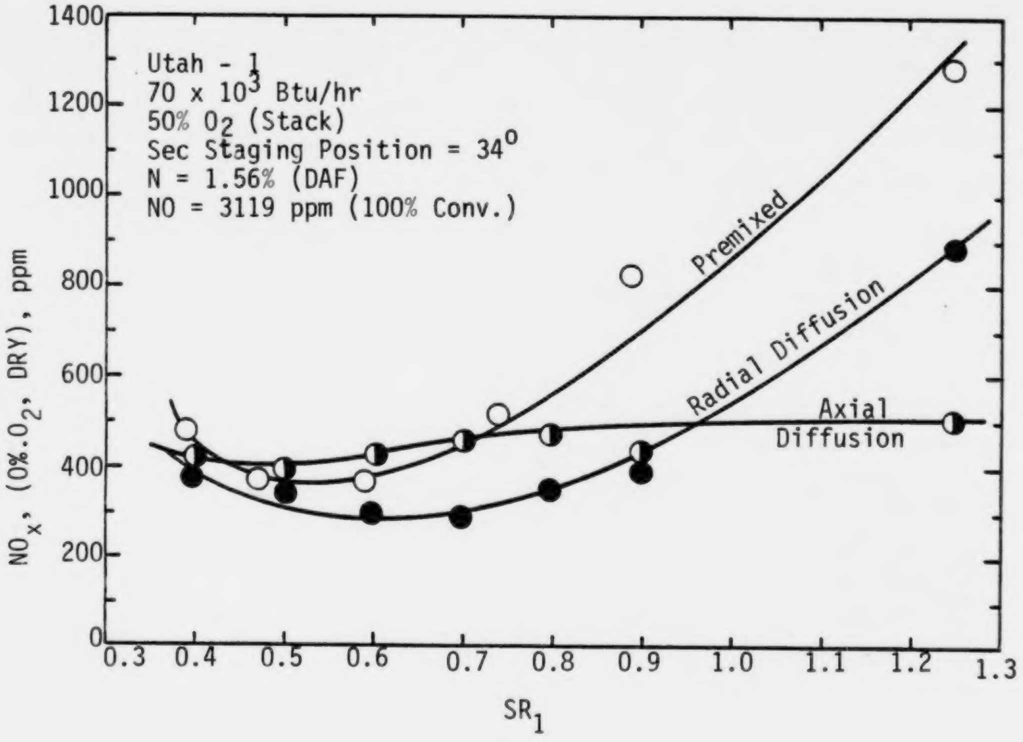
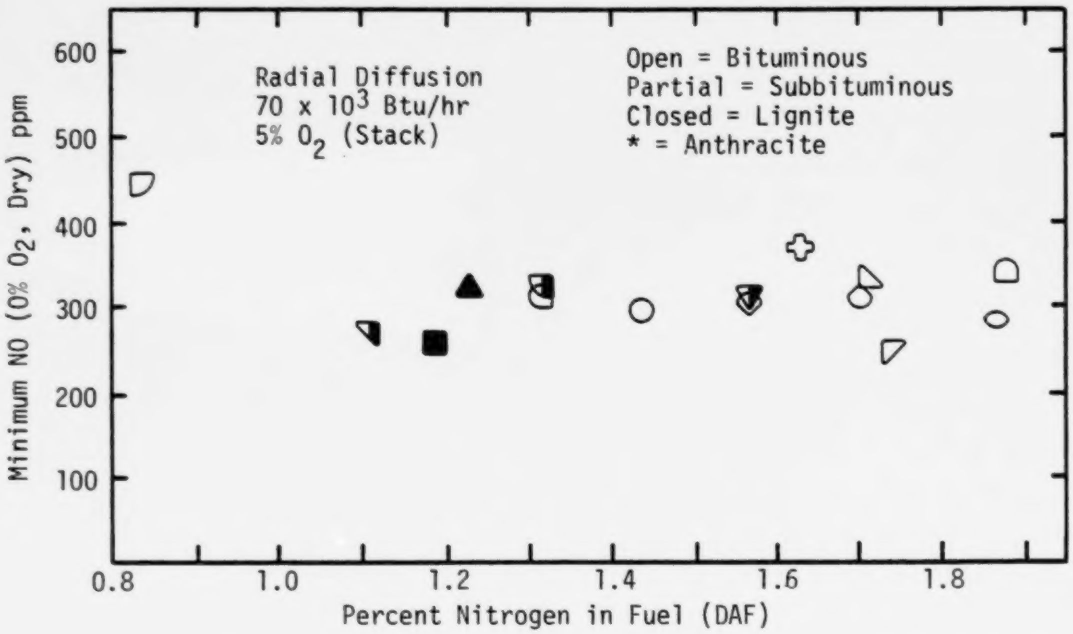


Figure 3-9. Effects of Staging for Utah I Bituminous Coal with Three-Burner Configuration in the Argon Furnace.



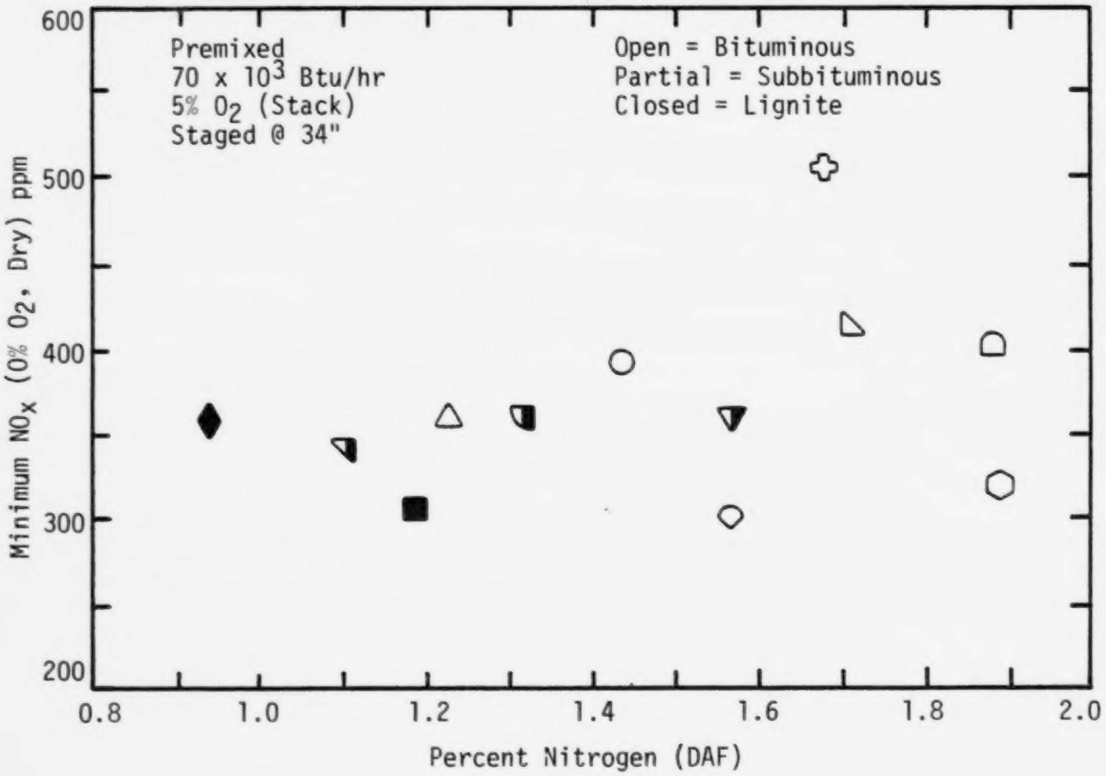


Figure 3-10. Summary of Minimum NO Concentrations with Staged, Premixed and Radial Diffusion Burners.

Figure 3-11 presents the minimum exhaust NO concentration as a function of the stoichiometric ratio of the primary zone for which that minimum value was achieved for both the premixed and the radial diffusion flames. When the data is presented in this way, the impact of fuel properties and the method of fuel/air contacting is much more dramatic; indeed, emissions are lower with the radial flame. However, the minimum emissions occur at less fuel-rich conditions. Also, fuel properties affect not only the minimum emission level, but also the stoichiometry at which that minimum was obtained. This latter impact may have more significance for operation of low NO_x combustors than does the variation in minimum emission level alone. The influence of initial fuel/air contacting conditions can be explained if it is remembered that even though the system is overall fuel-rich, the gaseous fraction is fuel-lean in the initial stages of the primary zone. Thus, under premixed conditions it requires a considerable residence time for the gas phase to achieve true fuel-rich conditions. With backmixing the initial zone has the characteristics more closely resembling the input stoichiometry.

3.1.4 Influence of Coal Properties

The ultimate goal and the experiments discussed above is the development of a capability to predict NO_x emissions under known combustion conditions as a function of coal properties. It is apparent that fuel NO_x formation is not solely dependent upon total fuel nitrogen content. Several attempts have been made to correlate the data based upon some property other than total fuel nitrogen content. Haebelt (3.1) has suggested that the coal oxygen content will influence fuel NO information, and has correlated emissions from corner-fired units by the oxygen-to-nitrogen ratio. The rationale behind this correlation is that for a given primary air mass flow rate then the availability of oxygen in the early stages of combustion will be influenced by the amount of oxygen contained in the fuel. Figure 3-12 compares the correlation obtained by Haebelt with the results obtained for the axial diffusion flame. This slowly mixing flame is most representative of the type of flame used in a corner-fired boiler. It can be seen that although emissions tend to increase with increasing oxygen/nitrogen ratio, this parameter alone is not sufficient to correlate the fuel NO formation. Indeed, coal oxygen-to-nitrogen ratio is largely a function of rank which affects other factors such as flame temperature and speciation of the coal volatiles.

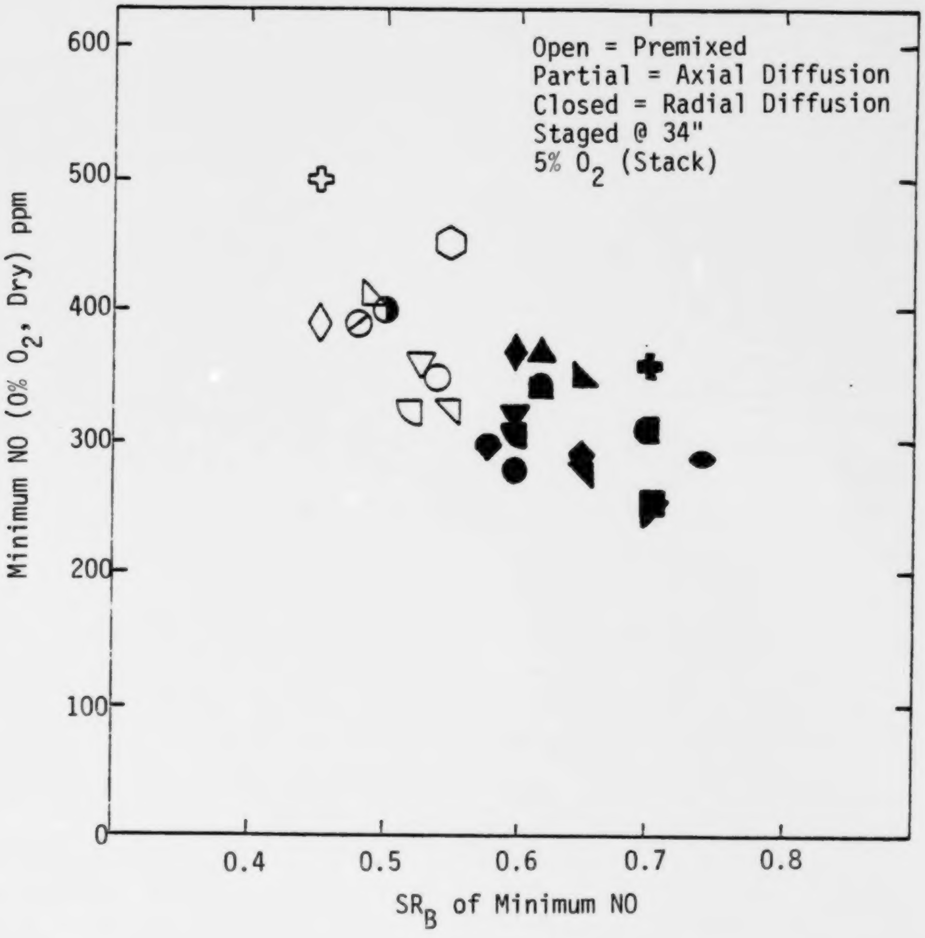


Figure 3-11. The Relationship Between Mixing and Optimum SR, for Different Fuels in the Small-Scale Furnace.

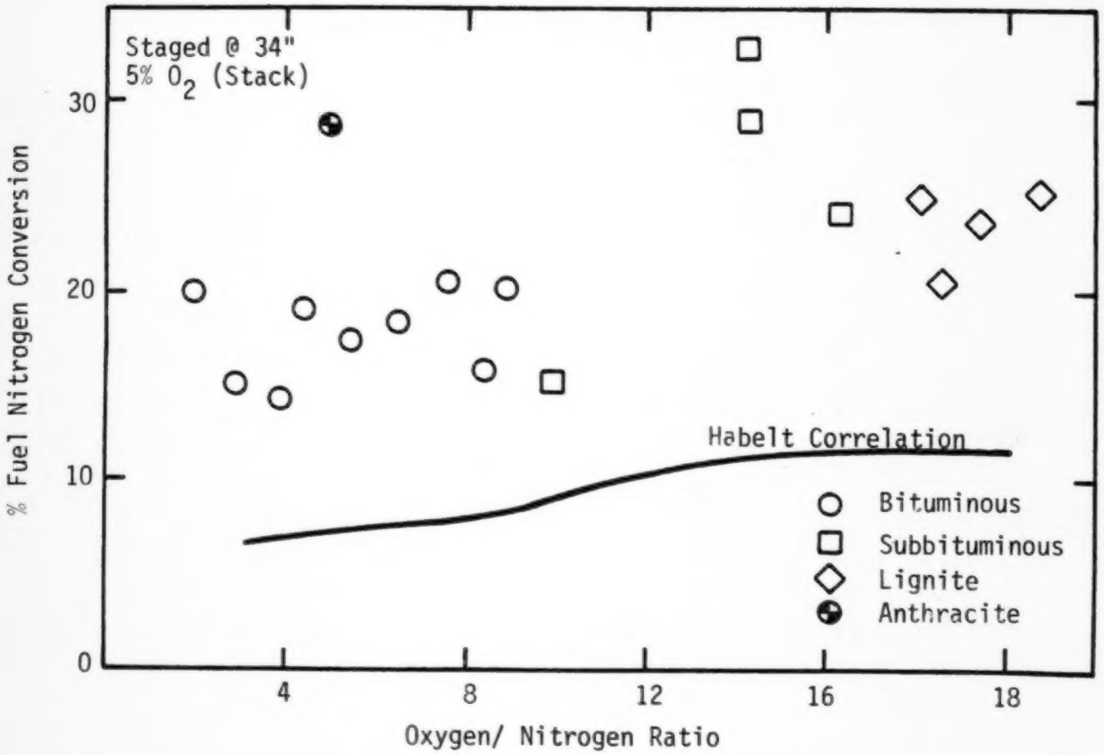


Figure 3-12. The Effect of Fuel Oxygen/Nitrogen Ratio on Fuel Nitrogen Conversion in Axial Diffusion Flames. Comparison with the Correlation of Habelt et al (3.1).

The earlier discussion included speculation that the fraction of the total fuel nitrogen that was volatile (i.e., emitted with the volatile fractions during thermal decomposition) had a major impact upon the formation of fuel NO. Thus, two simple experiments were carried out to determine whether volatile fuel nitrogen as determined either by the ASTM volatile matter procedure or by an inert pyrolysis experiment developed by Axworthy et al(3.2) under EPA sponsorship could be used as a technique for predicting fuel NO formation in pulverized coal flames. The char residue from an ASTM volatile test was analyzed for nitrogen content to determine the fraction of the nitrogen that had been liberated with the coal volatiles. Figure 3-13 shows the percent of nitrogen converted to NO under premixed conditions as a function of the nitrogen evolved with the ASTM volatiles. It can be seen that for the majority of coals more nitrogen is evolved during the volatile test than is converted to NO under combustion conditions. This is particularly true of the lignite coals. Anthracite shows very low nitrogen evolution during the ASTM volatiles test, and with the assumption that char nitrogen conversion is small, the results presented in Figure 3-13 indicate that the use of the ASTM tests to estimate volatile nitrogen is inadequate and that nitrogen evolution is much less in this test than occurs under flame conditions. Sarofim et al. have shown that nitrogen evolution is largely dependent upon the final particle temperatures, and since under combustion conditions particle temperatures far exceed those achieved during the ASTM test, volatile nitrogen loss should be higher under flame conditions. The results presented in Figure 3-13 suggest that this method of assessing volatile nitrogen evolution is not even capable of ranking fuels, and certainly not suitable as a predictive tool.

Axworthy et al. developed a pyrolysis reactor to investigate the conversion of fuel nitrogen to HCN under both inert and oxidative pyrolysis conditions. Gas phase kinetics experiments suggest that HCN is a reasonable model for volatile fuel nitrogen compounds; and therefore, the measure of fuel nitrogen that is converted to HCN could be indicative of the potential for a particular coal to produce fuel NO. The pyrolysis experiment was operated as a two-stage system. The fuel was placed in an initial reactor whose temperature could be varied, and the pyrolysis compounds were swept into a secondary reactor with an inert argon flow. This secondary reactor was maintained at 1100°C. Experiments have demonstrated almost quantitative conversion of nitrogen in pyridine to HCN at 1100°C.

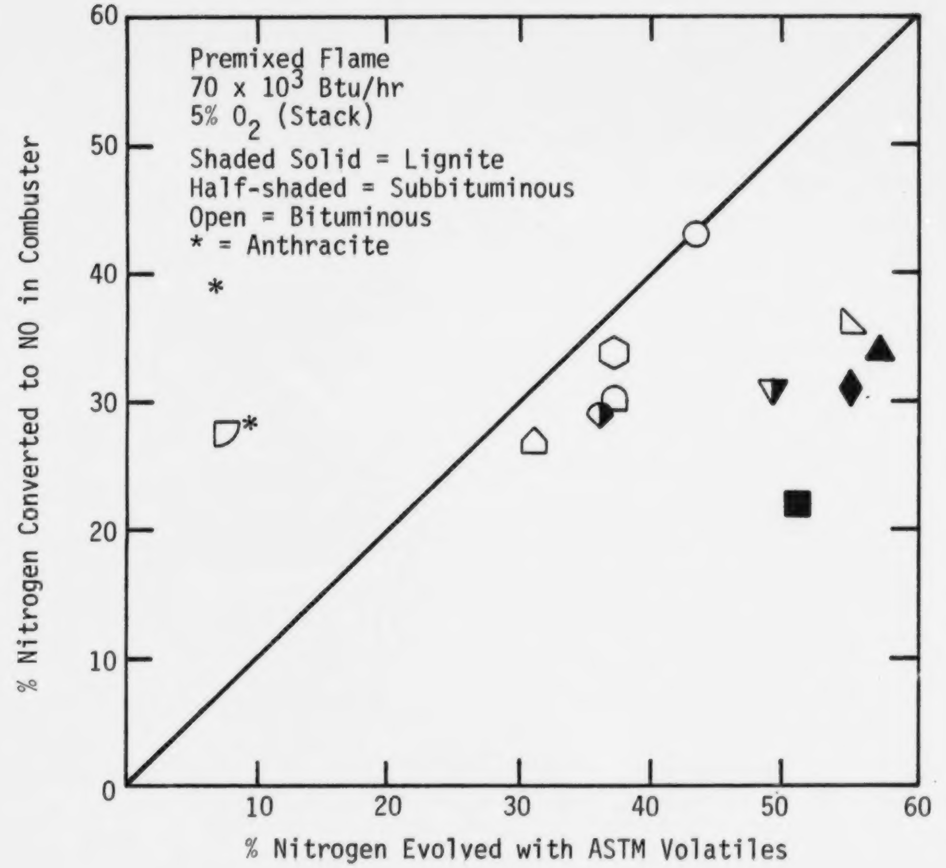


Figure 3-13. Volatile Nitrogen from ASTM, the Analysis and the Conversion of Fuel Nitrogen to Nitrate Oxides.

Thus, in this experiment, the fraction of fuel nitrogen capable of conversion to HCN could be assessed as a function of first-stage pyrolysis temperature. The results presented in Figure 3-14 compare the fraction of fuel nitrogen converted to NO for the three combustion conditions as a function of the fraction of the fuel nitrogen converted to HCN under pyrolysis conditions at 1100°C. It can be seen that the pyrolysis data agrees qualitatively with the experimental results obtained in the premixed and radial diffusion flames. The Savage lignite (Δ) gives the highest percentage conversion of fuel nitrogen to NO under combustion conditions, and also has the highest fraction of volatile nitrogen yield in the inert pyrolysis study. The slope of the correlation decreases with decreasing mixing rate (premixed to radial diffusion) as would be expected. Further experiments are being conducted by UTRC under sponsorship of the EPA's Fundamental Combustion Research Program (68-02-2631) in an attempt to more clearly define the influence of fuel properties on fuel NO formation.

3.2 Optimization of Staged Combustion Conditions

It is generally recognized that staged combustion offers the most cost-effective control technique for minimizing fuel NO formation. The basis for staged combustion as an NO_x control technique involves the competition between two reaction paths, one which forms N_2 and the other NO from the fuel-nitrogen species. The path producing N_2 is favored under fuel-rich conditions. Thermodynamic limitations indicate that the total fixed nitrogen specie (NO, NH_3, HCN) are a minimum at approximately 65 percent of the theoretical air requirements for complete combustion for most hydrocarbon fuels, and that this minimum concentration is of the order of 10 ppm under combustion conditions. Thus, it could be concluded that if all the nitrogen specie were in the gas phase then this thermodynamic limitation would represent the minimum NO achievable under staged combustion conditions, since it is reasonable to assume total conversion of these small TFN concentrations during second-stage burnout. Gas phase kinetics would also indicate that the approach to thermodynamic equilibrium is accelerated at high temperatures, even though the minimum TFN concentration would tend to increase. Staged combustion also has an impact upon the formation of fuel NO because the heat release process is extended in time allowing enthalpy loss, thus reducing peak temperatures.

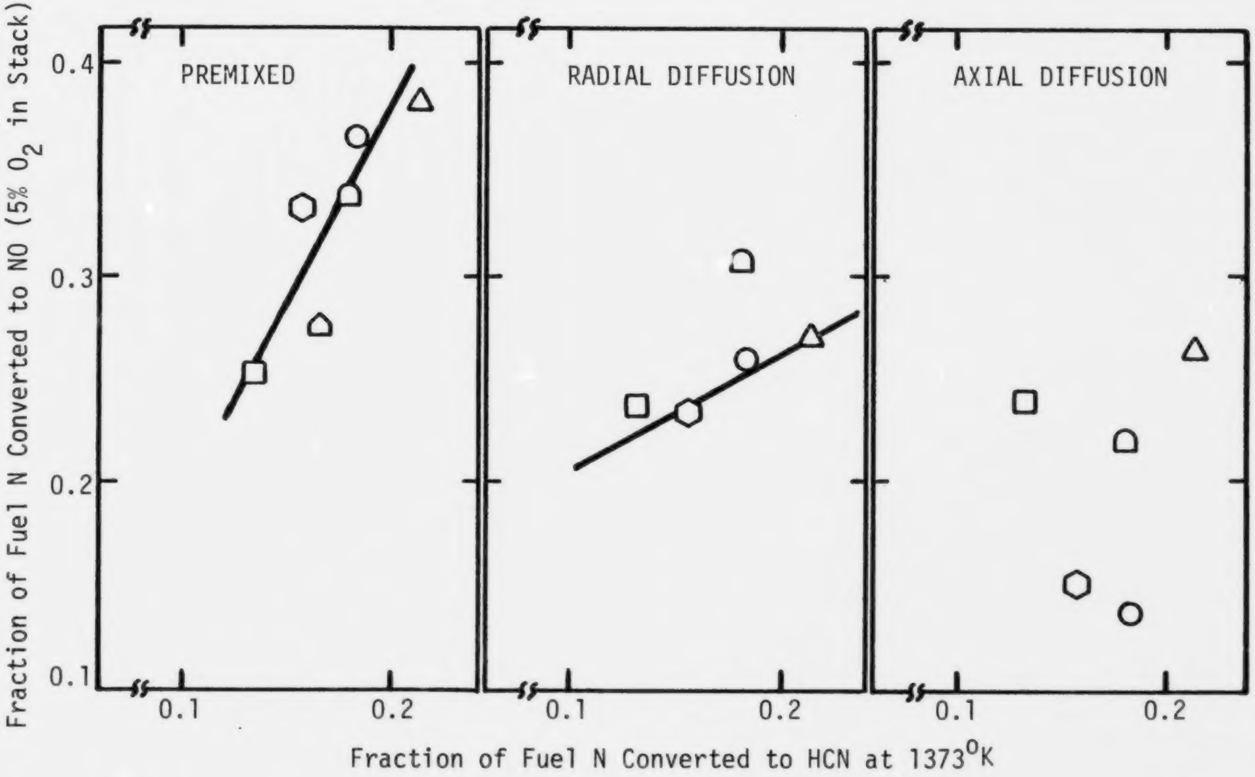


Figure 3-14. Fuel Nitrogen Conversion Can be Correlated by HCN Produced During Pyrolysis for Well-Mixed Combustion Conditions.

Staged combustion in coal is complicated because of the heterogeneous nature of the process. This has three implications:

- Nitrogen is contained in the solid and can be evolved either during thermal decomposition or remain with the char.
- The gas phase stoichiometry varies continuously with time from air to the input stoichiometry. Thus, even though the initial mixture is overall fuel-rich, the gas phase will remain oxidizing for some time until all of the oxygen has been consumed by the coal volatiles.
- The presence of solids (carbon or inorganic fly ash) may influence the rates of the reaction paths leading to N_2 or NO under certain conditions, and NO reduction by combustion products in the presence of solid carbon might become a factor under staged combustion conditions.

Bench-scale reactor studies provide an ideal opportunity to assess the impact of various control options on NO formation.

The primary control options are: (1) how rich, (2) how long, and (3) at what temperature? Two series of experiments have been carried out, one involving three-stage combustion and the other involving heat extraction in the fuel-rich first stage to allow more definitive experiments to be planned to optimize conditions for NO_x control via staged combustion.

3.2.1 Distributed Air Addition

Since it was recognized that gas-phase stoichiometry would vary with time, then the prevention of NO formation in the early stages of combustion could not be eliminated since the first fuel nitrogen fragments would be mixed in an oxygen-containing environment. However, the speed with which this oxygen is depleted would be dependent upon the overall stoichiometry, and would occur much more rapidly if the first stage was operated very fuel-rich. Further, air could then be added to provide the optimum-gas-phase stoichiometry for minimizing total fuel nitrogen concentration. Thus, a series of experiments were carried out in which the fuel-rich stage was divided into two sections. The first-stage stoichiometry and the overall excess air level were maintained constant (SR_t of 1.25 is equivalent to 5 percent oxygen in the stack) and the stoichiometry of the intermediate stage (SR_2) was varied in an attempt to investigate the impact of distributed air addition. Figure 3-15 illustrates the furnace configuration and summarizes the data obtained with a bituminous coal. The residence time for the two stages is shown in Table 3-2. Final NO emissions were reduced by approximately 15 percent by operating under three-stage conditions. However, it is somewhat surprising that the lowest emissions were achieved with a first-stage stoichiometry of 70 percent of theoretical air.

Data from other bituminous coals is presented in Figure 3-16, and Figure 3-17 presents data obtained for subbituminous lignite and anthracite coals. The same basic trends occur for all bituminous coals tested, although the effect of distributed air is dependent upon the type of coal tested. For both lignites and anthracites there appears to be a minimal return for operating the combustor in a three-stage condition. One problem with these preliminary investigations is that the influence of stoichiometry is not decoupled from that of temperature since temperature will vary with the stoichiometry of the various zones since it is dependent upon heat release.

3.2.3 The Effect of Heat Extraction

The bench-scale reactor was modified slightly to allow its operation with three independent zones as follows:

1. An initial fuel-rich zone that could be isolated from a down-stream section with a radiation choke.
2. A fuel-rich zone with and without heat extraction using removable cooling coils.
3. A second-stage air injection system which provided a choke prior to injection of the second-stage air to facilitate stabilization of the diffusion flame. The second-stage air could then be added either axially or radially to vary the mixing rate between the primary products and second-stage air.
4. A burnout zone with the possibility of heat extraction using removable cooling coils.

A schematic of the modified bench-scale reactor is shown in Figure 3-18.

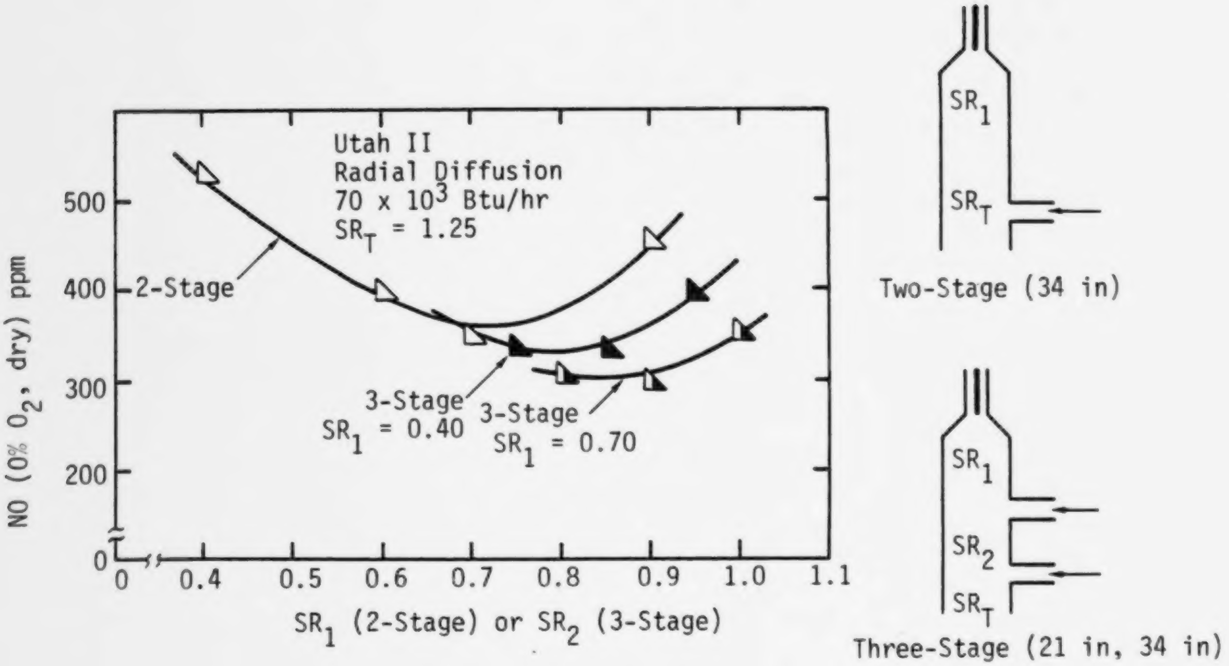


Figure 3-15. Influence of SR_1 in Three-Stage Combustion of Utah Bituminous Coal in Argon Furnace.

Table 3-2. Approximate Residence Times for Various SR_1 Values in Combustion

SR_1	Time (Sec)*	
	21 in	34 in
0.4	1.07	1.73
0.5	0.85	1.38
0.6	0.71	1.15
0.7	0.61	0.99
0.8	0.53	0.86
1.0	0.43	0.64
1.25	0.34	0.41

* Based upon an assumed bulk gas temperature of 2000°F.

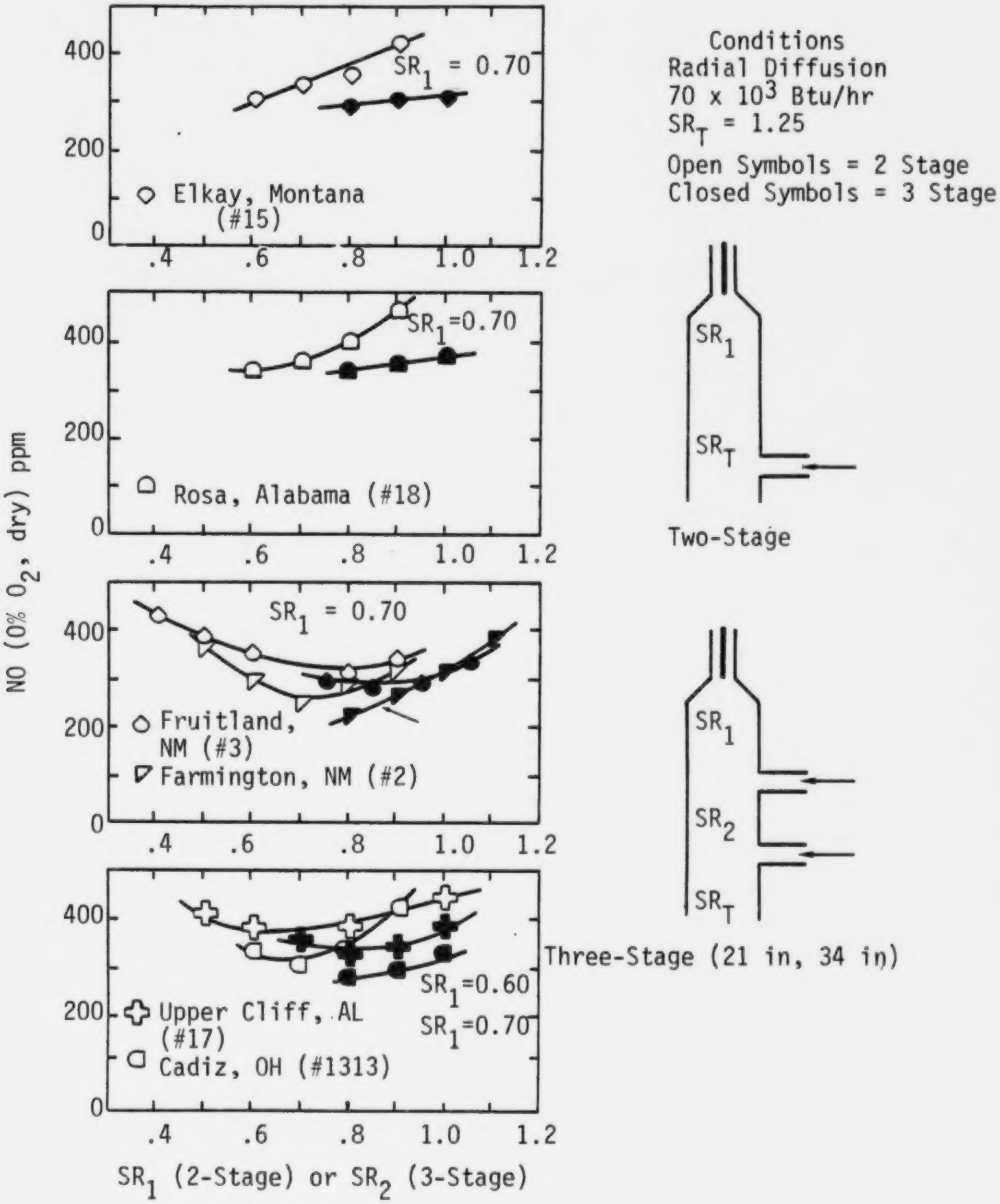


Figure 3-16. Summary of NO Emissions at 2- and 3-Stage Conditions For Bituminous Coals in Argon Furnace.

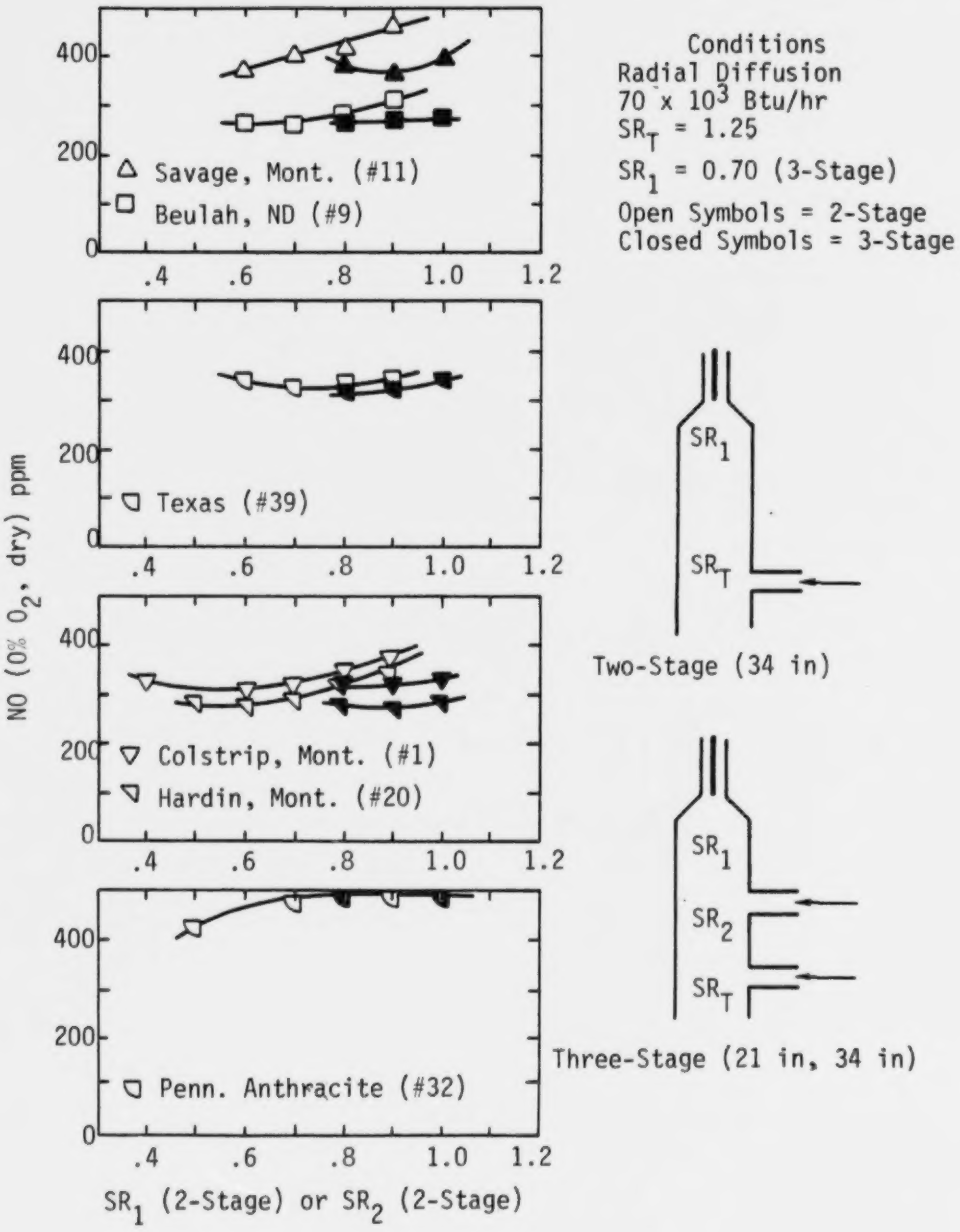


Figure 3-17. NO Emissions at 2- and 3-Stage Conditions for Subbituminous Lignite and Anthracite Coals in Argon Furnace.

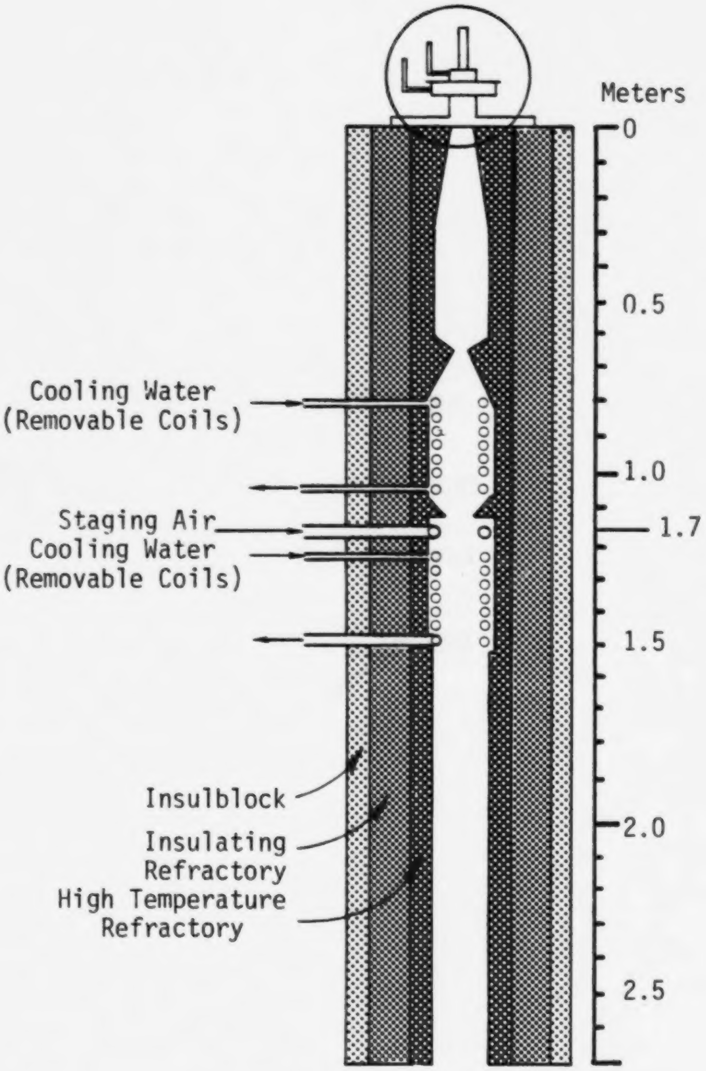

Meters
0
0.5
1.0
1.7
1.5
2.0
2.5
Cooling Water
(Removable Coils)
Staging Air
Cooling Water
(Removable Coils)
Insulblock
Insulating
Refractory
High Temperature
Refractory

Figure 3-18. Modified Bench-Scale Reactor.

In these experiments concentrations of NO, NO_2, HCN and NH_3 were measured in the fuel-rich zone. A water-quench probe was used to withdraw the samples, and HCN and ammonia concentrations were determined by ion-specific electrodes. Appropriate precautions were taken to minimize sulfide interference with HCN measurements.

Figure 3-19 compares final NO emissions achieved under staged combustion conditions with the bench-scale reactor operating in one of three modes. The minimum emissions were obtained when a cooling coil was inserted between the radiation choke and the staged air-addition choke. Maximum emissions were obtained without heat extraction; however, when heat was removed after addition of second-stage air, emission levels were intermediate between no heat extraction and heat extraction from the primary zone. These results are surprising since removal of heat from the first-stage should increase the total fixed-nitrogen concentration at the exit of the first-stage because the rate of the reactions forming N_2 are reduced, which should increase rather than decrease final emissions.

A series of in-flame measurements were carried out in order to check the hypothesis that the removal of heat from the first stage increases the total fixed-nitrogen content at the exit of fuel-rich stage. Figure 3-20 shows the concentration of NO, HCN and ammonia as a function of distance from the fuel injector for a first-stage stoichiometry of $SR_1 = 0.8$. It can be seen that the major impact of temperature is upon NO. Both HCN and ammonia concentrations are lower under cool conditions. Thus, removal of heat does increase the total fixed nitrogen specie, but the increase is largely accounted for in an increase in the fraction of NO.

Figure 3-21 summarizes the data obtained to date with one coal with the radial fuel injector. Removal of heat from the first-stage reduces final NO concentrations. However, it increases the gaseous total fixed-nitrogen specie exiting the fuel-rich first stage. Further experiments are currently underway, including measurement of char nitrogen and particle temperature to provide an explanation for this observation which is completely contrary to observations made with liquid fuels in a similar reactor.

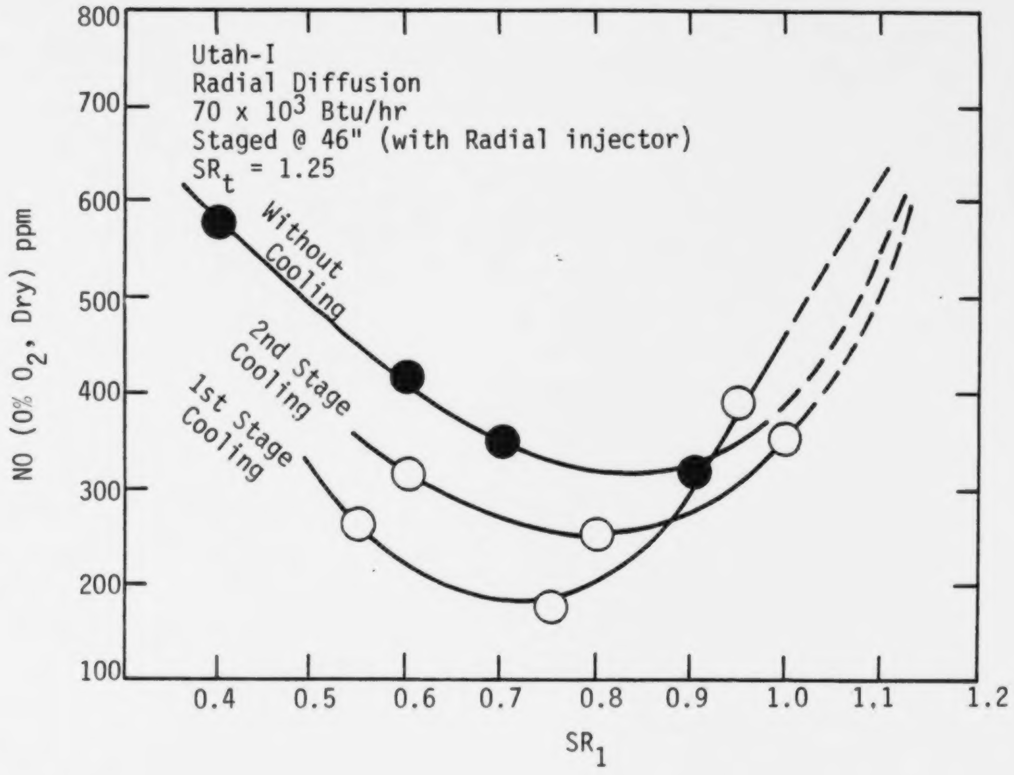


Figure 3-19. The Effect of Location of Heat Extraction Coils on Final NO Emissions as a Function of First Stage Stoichiometry.

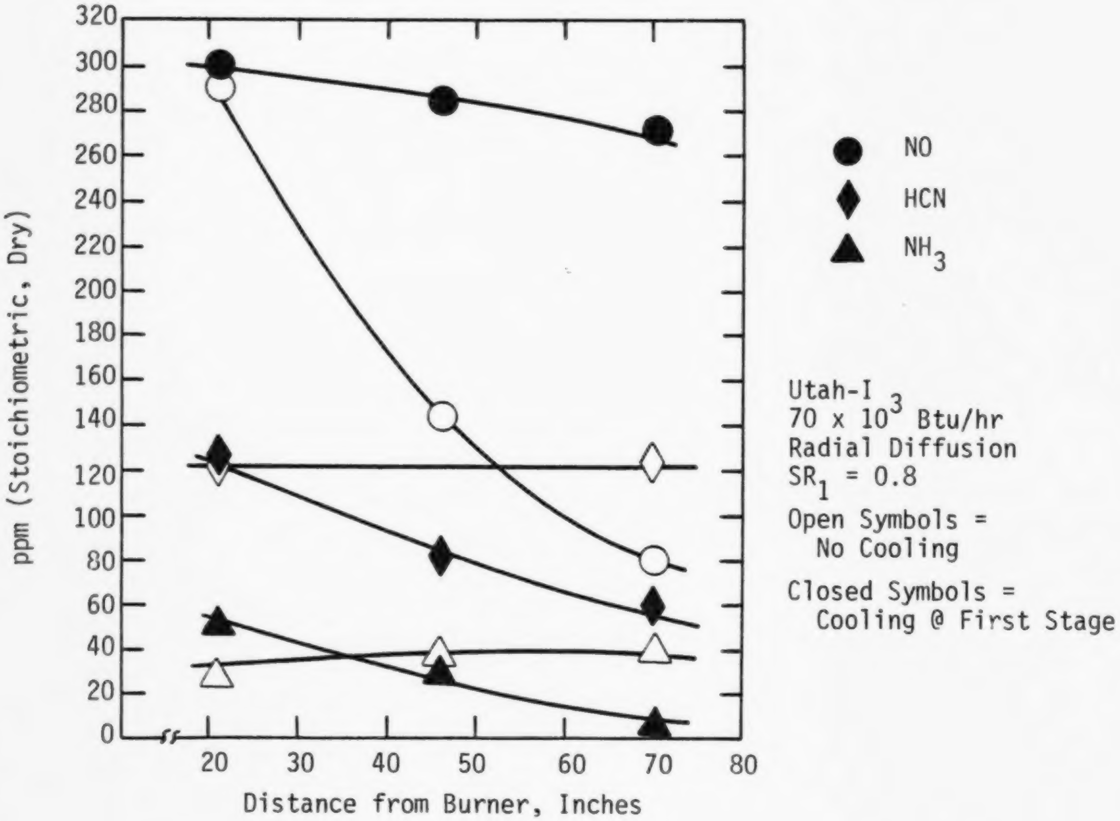


Figure 3-20. Variation of NO, HCN and NH_3 with Time.

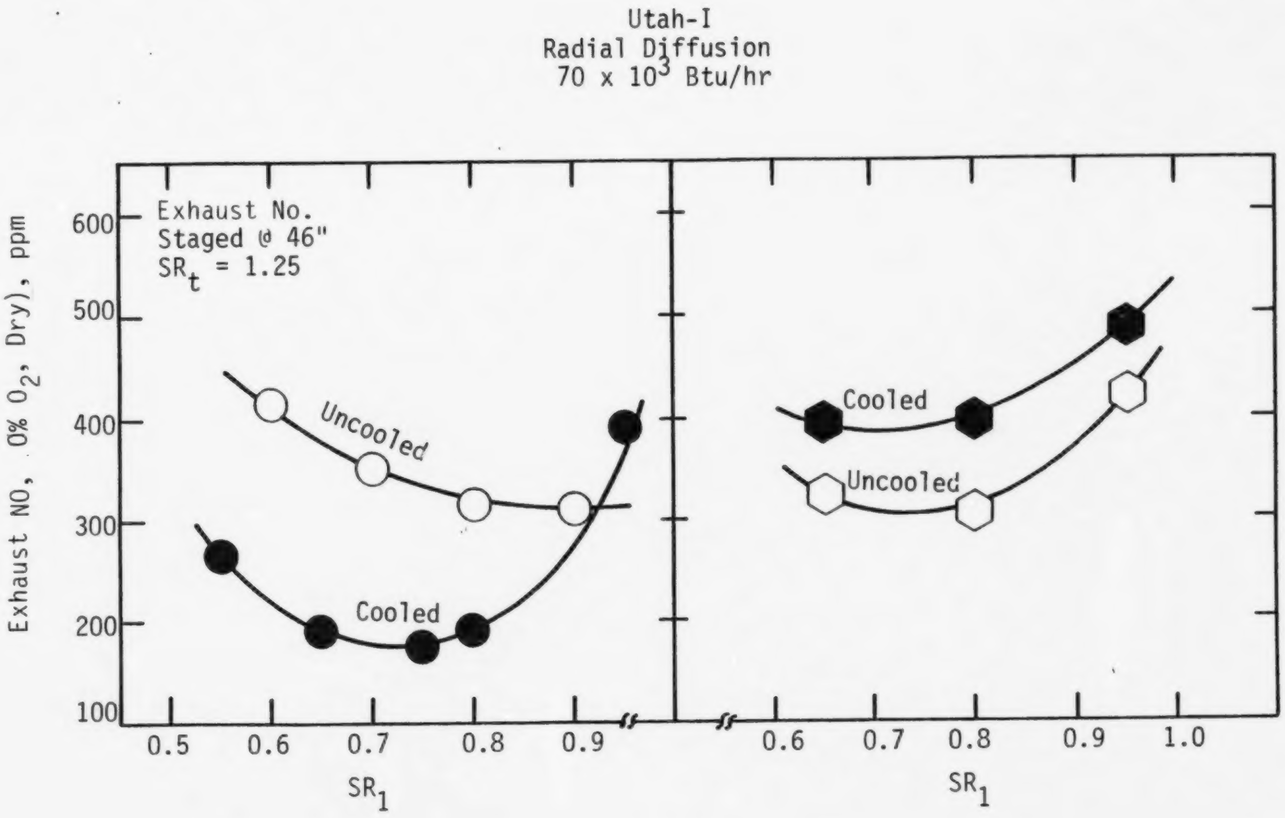


Figure 3-21. The Influence of Heat Extraction of Final Exhaust Emissions and Total Fixed Nitrogen at the Exit of the First Stage.

3.3 Concluding Remarks

Fuel Effects

The bench scale studies have demonstrated that fuel NO formation under excess air conditions, is very strongly dependent upon fuel/air contacting and upon the thermal environment of the particles, and it is not a simple function of total fuel nitrogen content. A series of preliminary experiments suggest that some simple procedure could be developed to determine the volatile fuel nitrogen fraction which would allow an assessment of the impact of fuel properties on the fuel NO formation. Absolute NO emissions, measured under staged conditions, are less dependent upon overall fuel nitrogen content than those measured under excess air conditions. However, fuel effects are still very important since they not only impact the final emission level, they also determine the stoichiometry at which that minimum occurs.

Future efforts should concentrate upon three major areas:

1. Extending information on the types of coals tested. Coals from several major fields have yet to be tested, and more coals will be tested in the next year which are representative of the bituminous coals obtained in the Mid-West and the Appalachian regions. It is also necessary to assess the impact of fuel properties on NO formation for cleaned coals and gasification chars.
2. The measurement of total fixed nitrogen species and char nitrogen content as a function of stoichiometry and temperature for a wide range of fuels.
3. Since thermal environment appears to have a considerable impact upon fuel NO formation. It might well be that fuel nitrogen formation is affected by the influence of coal properties on the particle temperatures. In the following series of studies, two-color pyrometry will be used to measure particle temperatures under a wide range of conditions.

Staged Combustion Optimization

The most significant result described in this section is the impact of heat-extraction in the first stage of the staged system on fuel NO emissions. These results are contrary to predictions based upon both gas phase chemistry and similar experiments with liquid fuels containing bound-nitrogen. In the following year the experiments involving heat extraction will be extended to include other fuels, as well as integrating the effects of both distributed air-addition and heat-removal.

REFERENCES

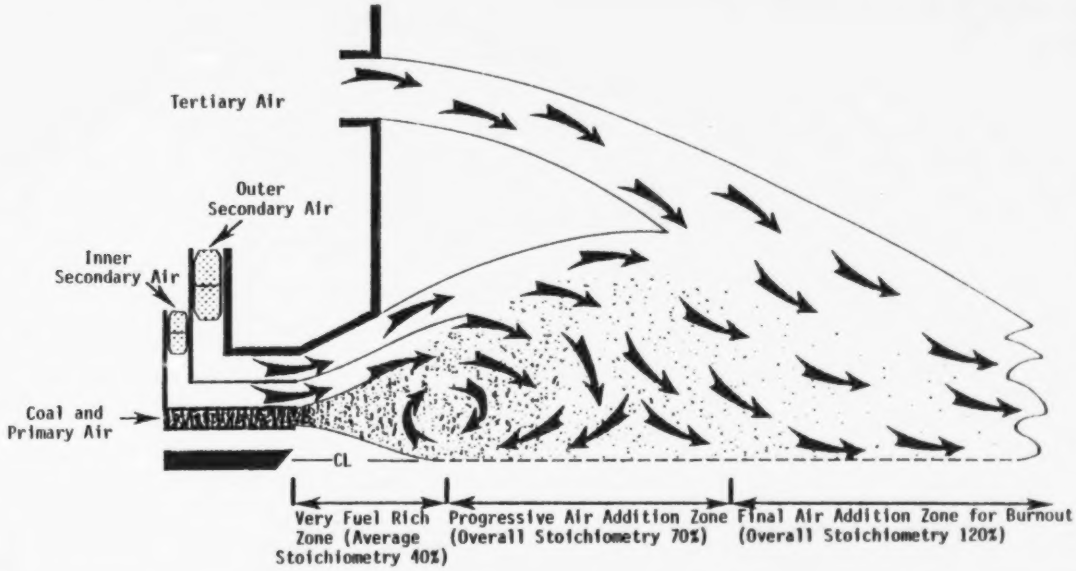
3.1 Habelt, W. W., "The Influence of Coal Oxygen to Coal Nitrogen Ratio on NO_x Formation," 70th Annual AiChE Meeting, New York, New York (1977).

3.2 Axworthy, A.E., Recht, H. C., Dayan, V. H., Gay, R. L., and Nealy, C. L. Volatility of Fuel Nitrogen, Final Report, Prepared Under EPA Contract 68-02-2631, Fundamental Combustion Applied to Pollutant Control.

4.0 DISTRIBUTED MIXING BURNER DEVELOPMENT

The DMB concept involves staging the combustion process to minimize NO_x emissions while maintaining an overall oxidizing atmosphere in the furnace to minimize slagging and corrosion. NO_x production from fuel nitrogen compounds is minimized by driving a majority of the compounds into the gas phase under fuel-rich conditions and providing a stoichiometry/temperature history which maximizes the decay of the evolved nitrogen compounds to N_2. Thermal NO_x production is also minimized by enthalpy loss from the fuel-rich zone which reduces peak temperature.

A schematic representation illustrating how the DMB design sequentially stages the fuel/air mixing is shown below. The combustion process occurs in three zones. In the first zone, pulverized coal transported by the primary air combines with the inner secondary air to form a very fuel-rich (30 to 50 percent theoretical air) recirculation zone which provides flame stability. The coal devolatilizes and fuel nitrogen compounds are released to the gas phase. Outer secondary air added in the second "burner zone" where the stoichiometry increases up to about 70 percent theoretical air. This is the optimum range for reduction of bound nitrogen compounds to N_2. Air to complete the combustion processes is supplied through tertiary ports located outside the burner throat. This allows substantial residence time


Tertiary Air
Outer Secondary Air
Inner Secondary Air
Coal and Primary Air
CL
Very Fuel Rich Zone (Average Stoichiometry 40%)
Progressive Air Addition Zone (Overall Stoichiometry 70%)
Final Air Addition Zone for Burnout (Overall Stoichiometry 120%)

in the burner zone for decay of bound nitrogen compounds to N_2 and radiative heat transfer to reduce peak temperatures. The tertiary ports surround the burner throat providing an overall oxidizing atmosphere and minimizing interactions between adjacent burners.

The DMB concept is one method that can be used to achieve the process requirements. Using this concept approach the design features which are used to provide controlled distributed fuel/air mixing are:

- The fuel Injector Design. The coal-plus-primary air is injected into the furnace either from a circular injector, an annulus, or from a divergent cone. The velocity is completely axial or injected with a swirling component provided either by swirl vanes in the primary jet or by introducing some tangential motion upstream of the fuel injector. These burner parameters provide highly uniformly mixed fuel with primary air to prevent the production of excessively-rich or excessively-lean zones.
- Swirl Component of the Secondary Air. The swirl component in the secondary airstream may be adjusted to provide for the correct size and strength of the internal recirculation zone.
- Velocity Ratio. Velocity ratio between the secondary and primary streams controls the rate of mixing in the initial fuel-rich stream.
- Burner Exit Geometry. The rate of divergence of the burner exit controls the properties of the internal recirculation zone.
- Location of the Outboard Staged Air Jets and Momentum. These dictate the residence time in the rich section as well as the time available for burnout.

In addition to providing those conditions which tend to minimize NO_x formation, all of these same parameters can be used to provide either a long flame or a short flame. The long flame is one method of minimizing NO by controlling the oxygen availability and maximizing residence time for conversion of XN to N_2. For many older conventional boilers, however, a long flame is not compatible with the available confinement; therefore, flexibility in adapting the flame to the shape required by the boiler furnace allows the optimization of the DMB concept in virtually all boilers. Also for new boilers, the long flame results in a limitation on the maximum burner liberation rate which results in an increase in the number of burners.

The information contained in this section is organized into two major subsections. In the first subsection, the single and multiburner efforts are discussed. In the final subsection, the total body of information is combined to establish general DMB design guidelines. It should be noted that the results and conclusions presented represent a current status of a continuing program and are, therefore, to be considered tentative at this time.

4.1 Single Burner Efforts

A summary of the various burner designs and variables studied is contained in Figure 4-1. The specific burner design concept information and operating characteristics are presented in Section 4.1.1. Section 4.1.2 describes the general impacts of burner input parameters and settings on both the NO and CO characteristics, while in section 4.1.3, the operating limits for the various burners are described and compared. Lastly, in Section 4.1.4 the impact of several fuels on burner operation are presented.

4.1.1 DMB Designs

Two basic distributed mixing burner configurations have been studied. Utilizing these two-design configurations, a total of five single-burners and one multiburner array were evaluated. The burners are:

- Dual Secondary Burner
  - Single burner capacities
    50×10^6 Btu/hr
- Single Secondary Burner
  - Single burner capacities
    10×10^6 Btu/hr

- FUEL SYSTEM VARIABLES
  - primary stoichiometry
  - primary air velocity
  - primary air swirl
  - coal nozzle setback
  - tangential/axial coal inlet

- AIR SYSTEM VARIABLES
  - tertiary air port location
  - tertiary air velocity
  - secondary air swirl
  - burner zone stoichiometry

- THROAT GEOMETRY VARIABLES
  - length of quarl
  - exit angle of quarl

- OPERATING VARIABLES
  - overall excess air
  - burner heat release
  - primary air temperature
  - secondary air temperature

- FUELS

- FLAME CHARACTERISTICS

- SCALE

- SINGLE/MULTI-BURNER CONFIGURATION

Figure 4-1. Burner and Operating Parameters Investigated.

12.5×10^6 Btu/hr
50×10^6 Btu/hr
100×10^6 Btu/hr

- Multiburner array

  2 X 2 array of 12.5×10^6 Btu/hr burners (total capacity of 50×10^6 Btu/hr)

4.1.1.1 Dual Secondary Burner

The dual secondary throat burner configuration is shown in Figure 4-2. The major features of this test burner are the following:

- Five independently-controlled airstreams divide the total combustion air into:

  (1) the primary air carrying the coal;

  (2), (3) two concentric secondary airstreams to provide for inner and outer secondary airflow; and

  (4), (5) four outboard staged airstreams which can be divided into the upper or lower injectors.
- A central fuel injector with a retractable oil gun on the burner axis.
- The swirl level of the secondary airstream in either of the two channels is controlled by varying the air flow through the adjustable swirl vanes. Thus, the total swirl level in either channel can be varied from zero to a maximum dictated by the angle of the adjustable swirl vanes.
- Interchangeable ceramic burner exits.

A complete set of dimensions for the 50×10^6 Btu/hr burner is presented in Table 4-1.

Figure 4-3 presents an operating map for the 50×10^6 Btu/hr dual secondary burner showing the air velocities in the burner passages as functions of the burner zone (primary plus secondaries) and overall stoichiometries and load. These calculations were based on fixed primary stoichiometry and a low sulfur bituminous coal with a heating value of 12,340 Btu/lb. In the sample

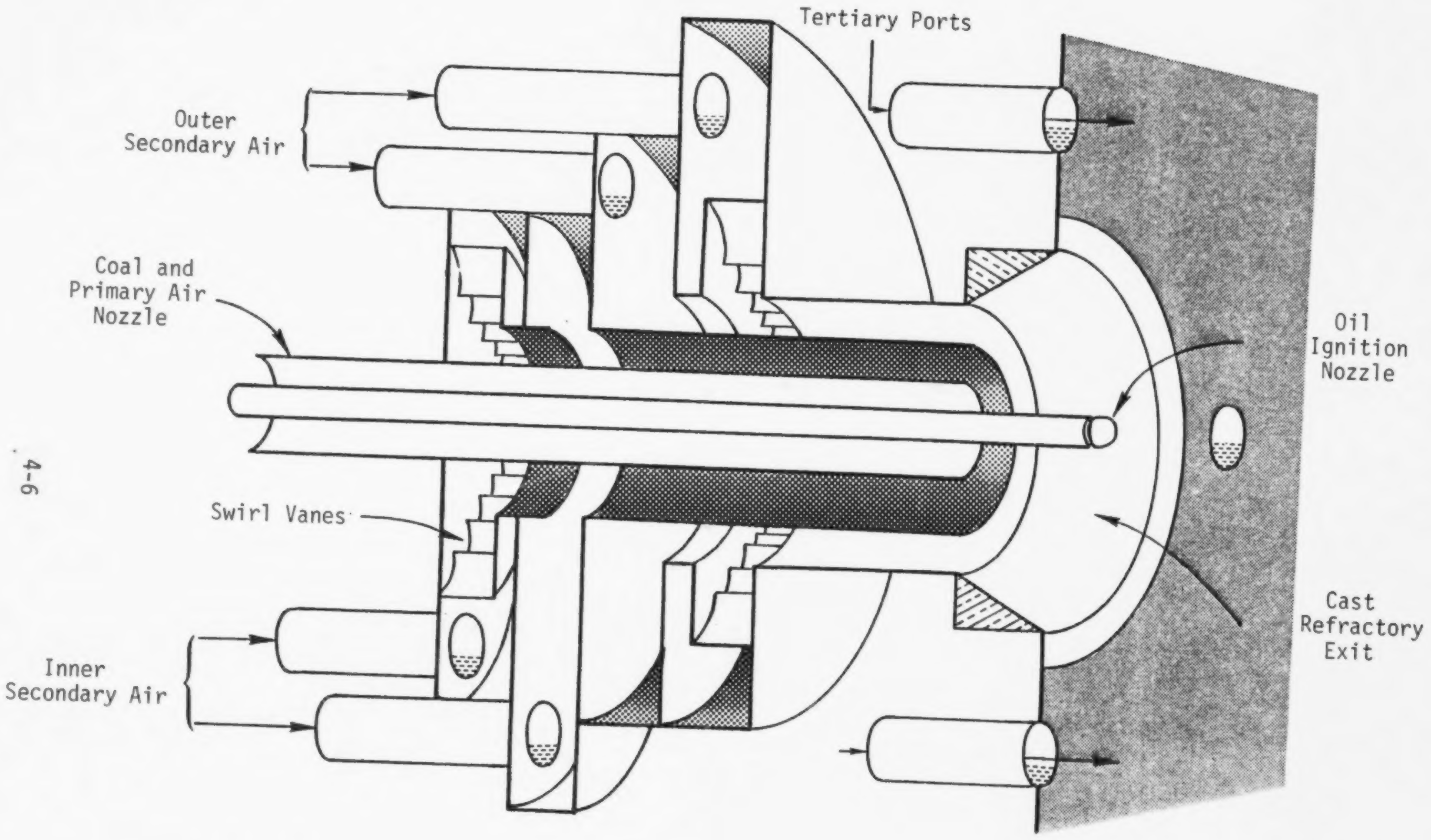

Tertiary Ports
Outer Secondary Air
Coal and Primary Air Nozzle
Oil Ignition Nozzle
Swirl Vanes
Cast Refractory Exit
Inner Secondary Air

Figure 4-2. Dual Secondary Throat Distributed Mixing Burner (50 x 10^6 Btu/hr).

Table 4-1. Design Information for Dual Secondary Burner.

Design Variable	Value
Fuel Injector	
Diameter (in)	9.0
Area (in^2)	63.6
Swirl Angle (degrees)	None
Setback (in)	0
Inner Secondary Channel	
Outer Diameter (in)	15.5
Annulus Thickness (in)	3.25
Area (in^2)	125.0
Setback (in)	0
Outer Secondary Channel	
Outer Diameter (in)	20.0
Annulus Thickness (in)	2.25
Area (in^2)	125.0
Setback (in)	0
Tertiary Ducts	
Distance from Burner Centerline (in)	45.0
Spacing Around Burner (degrees)	90
Number of Ports	4
Injection Angle (degrees)	0
Axial Position (in)	0
Diameter (in)	9.0
Total Area (in^2)	254.0
Throat and Exit	
Throat Diameter (in)	20.0
Throat Area (in^2)	314.0
Half Angle of Exit (degrees)	25
Length of Exit (in)	18.5

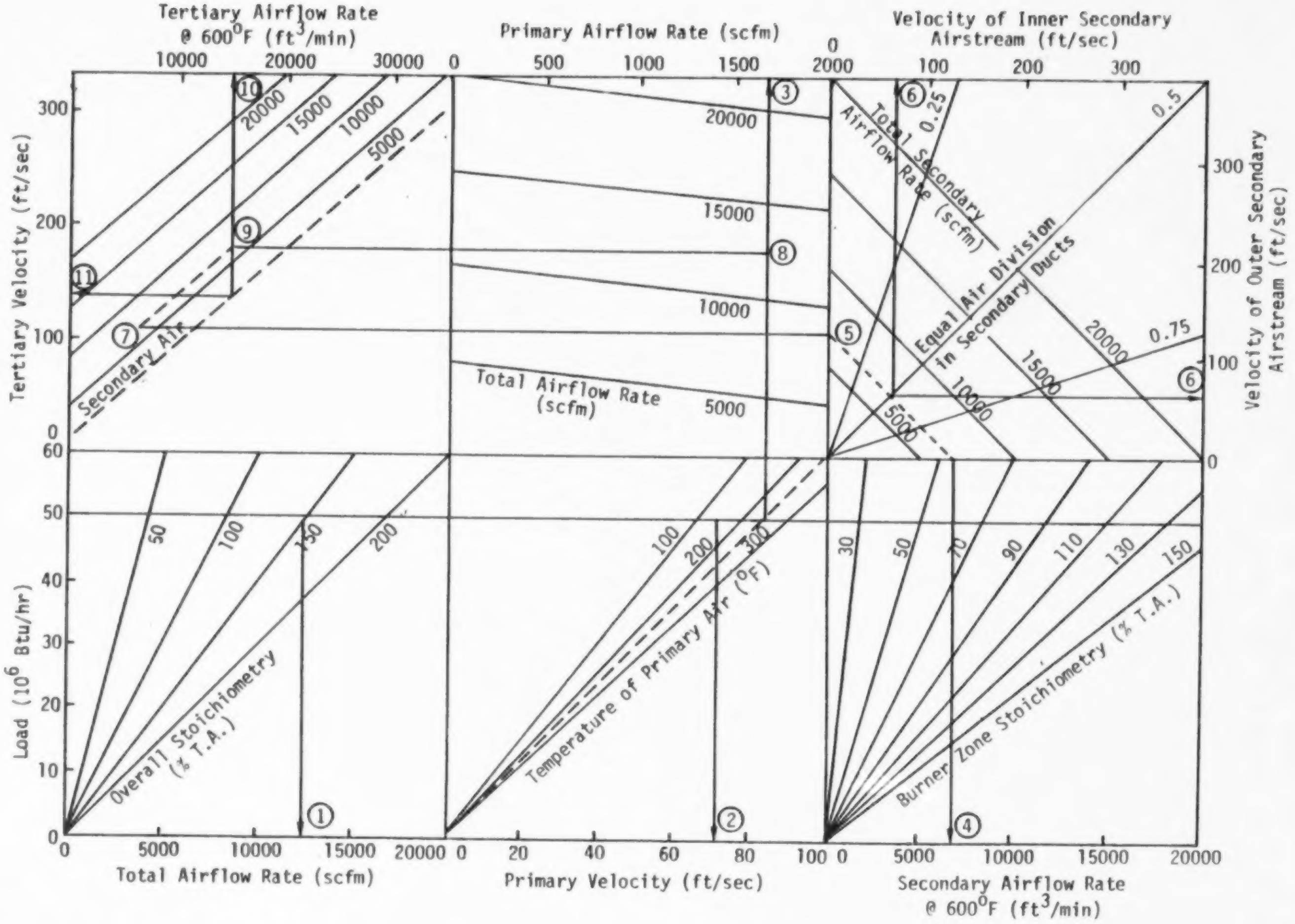


Figure 4-3. Operating Map for 50 M Btu/hr Dual Secondary Throat Burner with Utah Coal, Primary Stoichiometry 20% T.A. and Combustion Air Temperature 600°F.

case indicated on Figure 4-3 by "chase-around" lines and numbers, several operating conditions were first assumed. These were:

(1) Load = 50×10^6 Btu/hr

(2) Overall Stoichiometry = 150% T.A.

(3) Temperature of Primary Air = 150^{o}F

(4) Burner Zone Stoichiometry = 60% T.A.

(5) Fraction of Secondary Air in Outside Secondary Duct = 50%

With these five parameters fixed, all other burner flow parameters can be uniquely defined. (It should be noted that other combinations of parameters can also be chosen).

For this case the chart is entered (Lower Left Ordinate) at 50×10^6 Btu/hr and a horizontal line drawn completely across the figure. Where this line intersects the overall stoichiometry of 150 percent T.A.$_{D}$ the temperature of primary air of 150^{o}F and Burner Zone Stoichiometry of 60 percent T.A., the total Air Flow Rate ①, Primary Velocity ②, and Secondary Air Flow Rate ④ can respectively be determined. These values are:

Total Air Flow Rate = 12,500 Scfm

Primary Velocity = 72 ft/sec

Secondary Air Flow Rate = 7,000 ft^3/min

Due to the unique relationship between load and primary air flow rate (with the assumed primary stoichiometry of 20 percent T.A.) then the intersection of the load line with the dashed line in the center lower chart defines primary air flow rate ③ of 1,670 SCFM. To determine secondary flow parameters the upper right chart is entered by simply extending the vertical line which intersected the load and burner zone stoichiometry lines. The value of the total secondary air flow rate ⑤ can then be determined by interpolation between the two bracketing parallel lines. The value of total secondary air flow rate is 7,000 SCFM. Also, at the intersection of the dashed line which represents the total secondary air flow rate and diagonal line indicating the assumed split between the inner and outer secondary channels of 50 percent, the velocities of the inner and outer secondary flow rates ⑥ are defined as 70 ft/sec and 70 ft/sec respectively. The remaining variables to be defined are those associated with the tertiary air. The tertiary air flow rate and velocity are defined by first locating in the upper middle charter the intersection of the vertical line defining the primary air flow rate and the value previously determined for total air flow rate (12,500 SCFM) ⑦ and then proceeding horizontally and entering the upper left chart until the line intersects the previously determined value of the total secondary air flow rate (7,000 SCFM) at ⑧. The tertiary air flow rate is then determined directly from the upper scale at ⑨ and is 15,000 ft^3/min. Finally, the teriary air velocity is defined by first extending the vertical line which defined the tertiary air flow rate until it intersects the dashed diagonal line at ⑩ and reading from the ordinate at ⑪ the tertiary air flow rate is 140 ft/sec.

Use of this chart allows the engineer to quickly determine the impacts of varying specific burner flow parameters on the remaining variables. For example, referring to Figure 4-3, it can be seem that as the burner zone stoichiometry becomes more fuel-rich, the velocities in the secondary air channels are reduced. However, the velocity in one secondary air channel can be maintained constant by diverting air from the other channel. Although Figure 4-3 provides values for secondary velocities, the calculations only consider the axial components. As shown in Figure 4-4, the 50 x 10^6 Btu/hr burner allows a wide variation in the distribution of both axial and tangential velocity in the secondary airstreams via the variable independent swirl in each of the two channels. It is important to note from the information presented in Figure 4-3 that with fixed geometry, it is not possible to vary a single parameter independent of all others. As a consequence, optimization of performance and emissions will be specific to this test burner; however, the trends should be valid for all DMB designs.

The ability to vary secondary swirl over a wide range provides for considerable control over flame shape and the three basic flow patterns shown in Figure 4-5a were observed in both cold and hot-flow testing. These were:

- Type A with all axial flow except for an annular toroidal recirculation zone, which provided for flame stability.
- Type B with an axial toroidal recirculation zone.
- Type C in which the flow attached to the combustion chamber wall produced a wall jet.

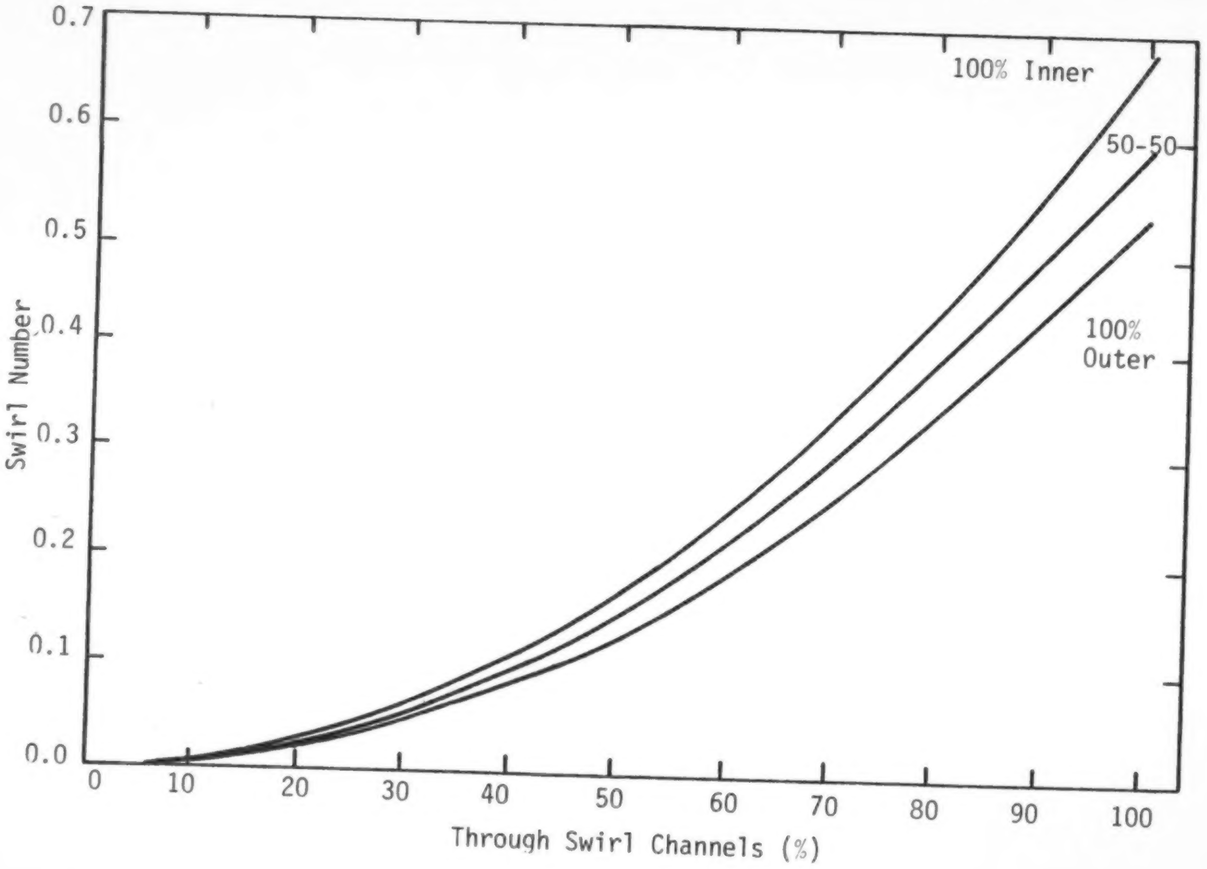
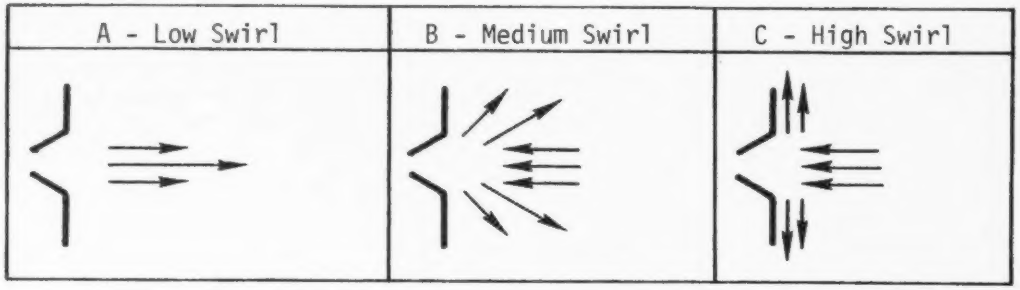


Figure 4-4. Swirl Number for Dual Secondary Throat Burner (50 MBtu/hr).

A. Flame Types


A - Low Swirl
B - Medium Swirl
C - High Swirl

B. Low NO_x Flame Shape - High Fineness Ratio Diffusion Flame

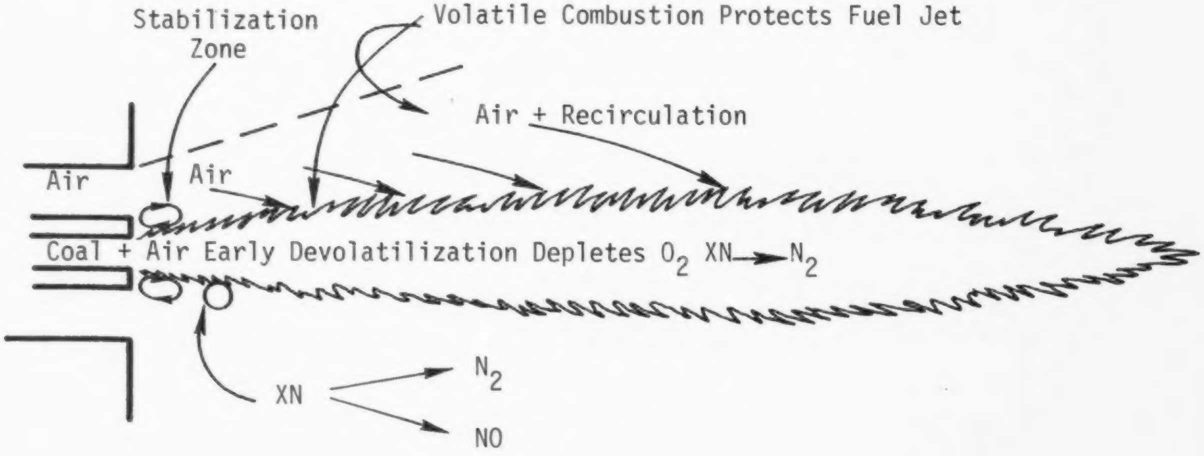

Stabilization Zone
Volatile Combustion Protects Fuel Jet
Air + Recirculation
Air
Air
Coal + Air Early Devolatilization Depletes O2 XN → N2
XN
N2
NO

Figure 4-5. Flame Characteristics with Divided Throat Burner.

The transition from A through C occurred as the swirl level in the outer channel increased. Low NO_x operation with this burner was generally achieved with a relatively long diffusion type A flame, as shown in the sketch on Figure 4-5b. In the combustor configuration employed in the tests with the 50 M Btu/hr burner, wherein the back wall was 16 feet from the firing wall, under some conditions the flame would impinge on the back wall. This condition accompanied increased buildup of residue in the bottom of the furnace, as well as increased opacity of the flue gases exiting the unit. Therefore, this burner was generally tested only at conditions where the wall impingement did not result in significant amounts of black smoke.

4.1.1.2 Single Secondary Burner

The single secondary burner design shown in Figure 4-6 incorporates the following features:

- Three independently-controlled airstreams to divide the total combustion air into:
    - the primary air carrying the coal,
    - a concentric secondary airstream,
    - four outboard staged airstreams.
- A central fuel injector with a retractable oil gun on the burner axis.
- Swirl vanes at the exit of the fuel nozzle to control the rate of mixing of the fuel into the secondary airstream.
- The swirl level of the secondary airstream was controlled by varying the adjustable swirl vanes. Thus, the total swirl level can be varied from zero to a maximum dictated by the angle of the adjustable swirl vanes.
- Interchangeable ceramic burner exits.

The single secondary burner shown in Figure 4-6 is a simple design incorporating practical features to provide ease of manufacture and operation, and to allow for the most straightforward interpretation of results. In order to develop scale criteria, the burners were designed at 10, 12.5, 50 and 100 x 10^6

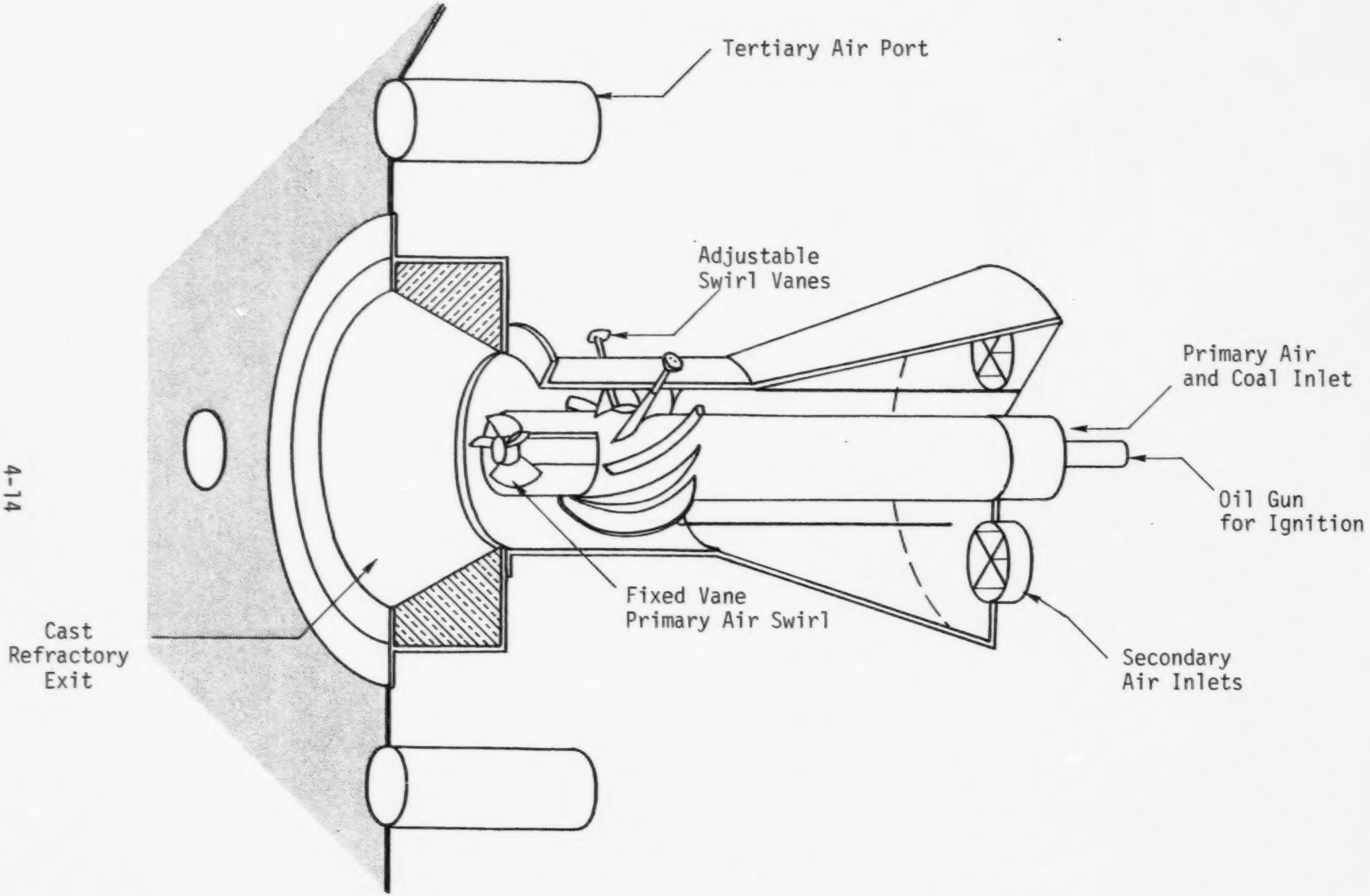

Tertiary Air Port
Adjustable Swirl Vanes
Primary Air and Coal Inlet
Oil Gun for Ignition
Fixed Vane Primary Air Swirl
Secondary Air Inlets
Cast Refractory Exit

Figure 4-6. Single Secondary Burner Design.

Btu/hr firing rates. The principle of geometric similarity with constant velocity was used for scale design. The four scales of burner each employed similar distributions of tangential velocity and similar locations of tertiary air inlets, although the 10×10^6 Btu/hr burner utilized the swirl method employed for the dual secondary burner. Further, the 10×10^6 Btu/hr burner did not employ a swirl vane in the coal nozzle. A summary of the specific design dimensions for each burner is provided in Table 4-2.

Figure 4-7 shows an operating map for the 50 Btu/hr version of the single secondary burner design. This figure is similar to that of the previous burner; however, the single secondary passage results in less complexity. The general flow characteristics and limitations are similar. In the example shown in Figure 4-7 the assumed conditions are:

(1) Load - 50×10^6 Btu/hr

(2) Overall stoichiometry - 125% T.A.

(3) Primary Air Temperature = 150^0F

(4) Burner Zone Stoichiometry = 70% T.A.

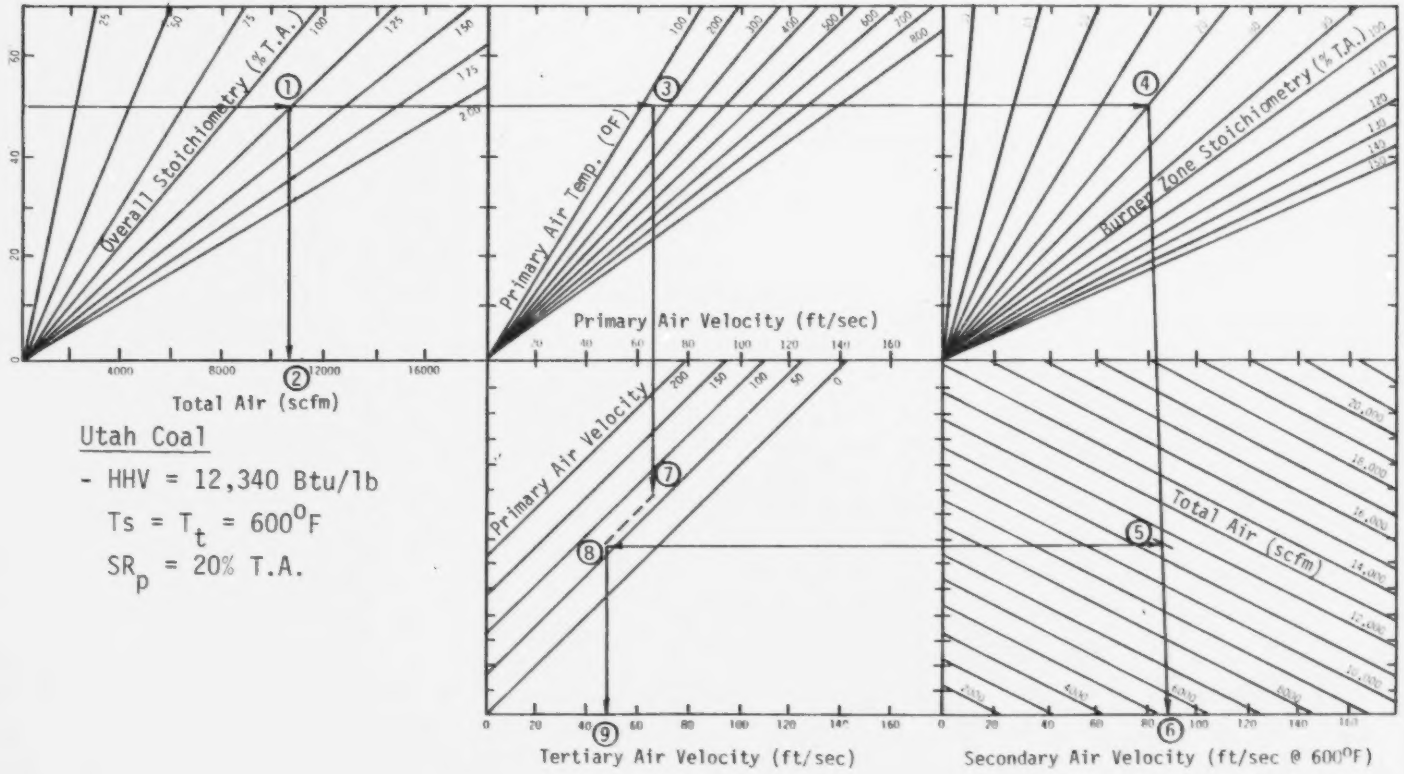
The horizontal line drawn at 50×10^6 Btu/hr intersects the other above parameters at ①, ③, and ④ allowing determination of the total air flow rate at ② of 10,600 SCFM, the primary air velocity at ⑤ of 70 ft/sec and the secondary air velocity at ⑥ of 88 ft/sec. The remaining parameters are then easily determined; for example, the Tertiary Air Velocity is determined by extending the horizontal line intersecting the Secondary Air Velocity with the previously determined Total Air flow rate (10,600 SCFM) until it intersects the previously determined primary air velocity indicated by the diagonal lines at ⑧. Note that the Tertiary Air Velocity can then be directly determined at ⑨ as 50 ft/sec.

A graph of the swirl index (calculated ratio of tangential to axial momentum) versus primary zone stoichiometry for two swirl angles (0 and 45 degrees) are shown in Figure 4-8. As with the dual secondary throat, this flexibility allowed the three basic flow patterns previously described to occur. With the added flexibility of spreading the coal into the secondary air, however, a much shorter flame was achieved while maintaining the low NO_x

Table 4.2. Design Information For Single Secondary Burners

Design Variable	Burner Capacity (10^6 Btu/Hr)			
	10	12.5	50	100
Fuel Injector				
Diameter (in)	5	5.5	10.5	15.75
Area (in^2)	19.63	24	86	195
Swirl Angle (Degrees)	Variable	45	45	195
Setback (in)	0	0	0	0
Secondary Air Channel				
Outer Diameter (in)	9.5	10.5	20	28
Annulus Thickness (in)	4.5	2.5	4.75	6.1
Area (in^2)	51.25	63	228	421
Swirl Vanes (degrees)	Variable	60	60	60
Setback (in)	0	0	0	0
Tertiary Ducts				
Distance from Burner C.L. (in)	-	22	44	62
Spacing Around Burner (degrees)	22.5	90	90	90
Number of Ports	16	4	4	4
Injection Angle (degrees)	0	0	0	0
Axial Position (in)	0	0	0	0
Diameter (in)	4.5	6	12	16
Total Area (in^2)	254.5	113	452	804
Throat and Exit				
Throat Diameter (in)	9.5	10.5	20	28
Throat Area (in^2)	71	87	314	616
Half Angle of Exit (degrees)	25	25	25	25
Length of Exit (in)	9	9 (18.5)*	18.5	27

*Alternate Exit Length to Match 50 x 10^6 Btu/Hr Burner Residence Time



Utah Coal

- HHV = 12,340 Btu/lb

$T_s = T_t = 600^{o}F$

SR_p = 20% T.A.

Figure 4-7. Operating Map for Burner Air Velocities for Various Loads and Overall Stoichiometry 50 M Btu/hr Single Secondary Burner Design.

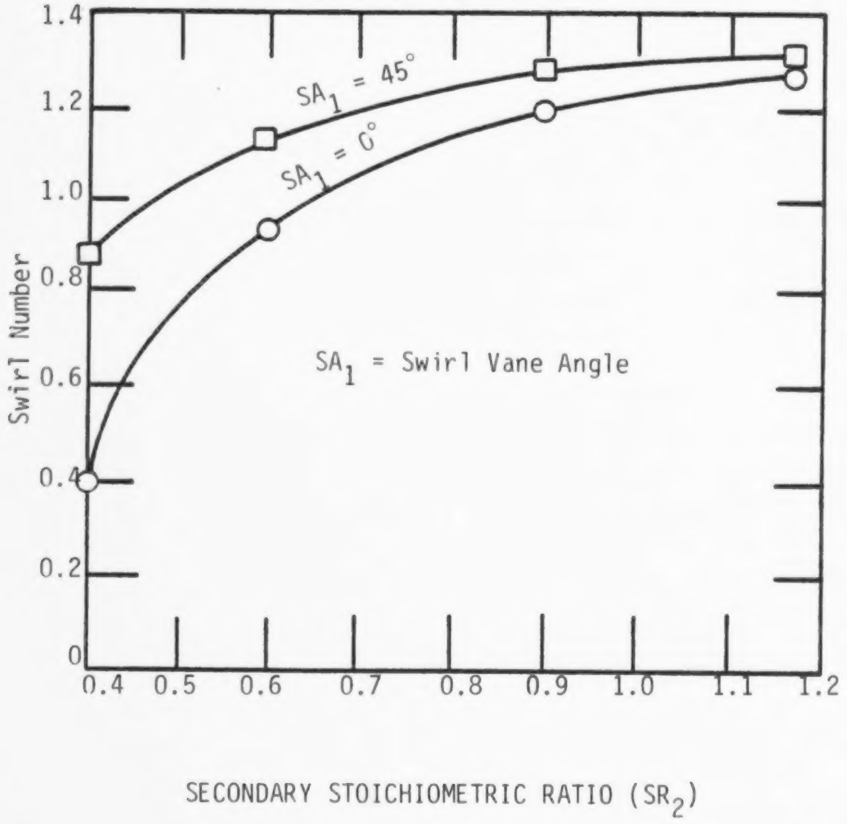


Figure 4-8. Swirl Characteristics for the Single Secondary Burner Design.

characteristics. A sketch of the flame shape is given in Figure 4-9. It should be noted that the shorter flame is compatible with most older boiler designs. The importance of this result is that low NO_x DMB designs can accommodate a broad range of boiler sizes since the flame shape/length can be varied from long diffusion-type flames compatible with deep furnaces including opposed-fired boilers to much smaller single wall-fired boilers.

4.1.2 DMB Subsystem Design Specifications

This section presents the results of development DMB tests in the research furnaces at EER leading to the specification of design criteria for the prototype DMBs. Six DMB configurations were tested in two research furnaces. The DMB designs are listed in Table 4-3 and are categorized as either long or short flame designs. The long flame designs utilized a central coal nozzle producing an axial coal and primary air jet which extended a considerable distance into the furnace. The resulting flames were long and narrow. The short flame designs also utilized a central coal nozzle but were equipped with an impeller to impart some swirl to the primary coal and air stream. As a result, the coal mixed more rapidly with the secondary and tertiary combustion air producing a shorter flame.

The burner design variables can be organized into the following four categories:

- Fuel Variables
  - Primary Temperature
  - Primary Stoichiometry
  - Primary Velocity
  - Primary Swirl
- Secondary Air Variables
  - Temperature
  - Burner Zone Stoichiometry (sum of primary and secondary)
  - Inner Swirl
  - Outer Swirl
  - Axial Velocity
  - Inner/Total Area
  - Inner/Total Flow Rate

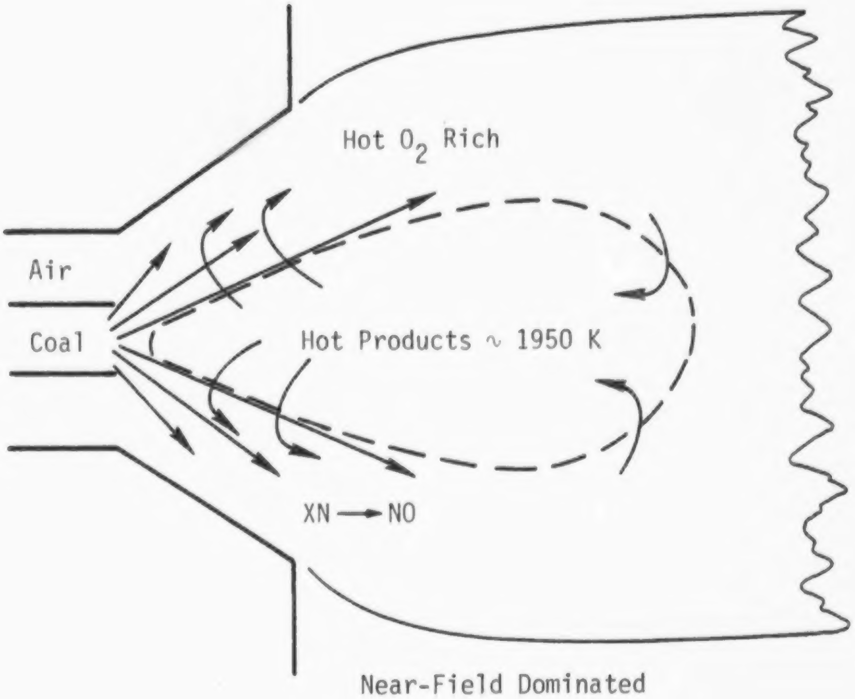

Hot O_2 Rich
Air
Coal
Hot Products ~ 1950 K
XN → NO
Near-Field Dominated

Figure 4-9. Typical Flame Shape for Single Secondary Burner.

Table 4-3. Development DMBs Tested in Research Furnaces

Flame Type	Burner Capacity (10^6 Btu/hr)	Burner Array	Number of Secondary Air Passages	Research Furnace
Long	10	1	1	SWS*
Long	50	1	2	LWS**
Short	12.5	1	1	SWS
Short	50	1	1	LWS
Short	100	1	1	LWS
Short	12.5	2 x 2	1	LWS

*SWS = Small Watertube Boiler Simulator Furnace: See Appendix B.

**LWS = Large Watertube Boiler Simulator Furnace: See Appendix B.

- Tertiary Air Variables
  - Temperature
  - Swirl
  - Axial Velocity
  - Angle
  - Number
  - Location
  - Divergence
- Exit Geometry
  - Half Angle
  - Length/Diameter
  - Setback - Inner Secondary
  - Setback - Outer Secondary

The test results presented in this section have been organized to delineate the effects of these variables on DMB performance. However, it should be noted that many of these variables are related and cannot be varied independently. For example, the primary velocity, nozzle diameter, primary stoichiometry, coal composition and firing rate are interrelated. Variation of any one of these variables will result in commensurate variations in one or more of the others. During the experimental effort, specific design parameters were varied two ways (when possible) to more clearly determine the effects on burner performance. The tests were primarily conducted firing Utah, low sulfur high volatile bituminous coal at 100 percent of the design firing rates (full load). Additional tests were conducted with other fuels at off design point operating conditions to verify that the DMB could be operated over a wide range of conditions.

4.1.2.1 Fuel System Variables

The fuel system includes the fuel/air characteristics through the burner fuel nozzle (primary stoichiometry, etc.) and fuel nozzles geometric variables. Typical parameters include:

1. Primary transport fuel/air stoichiometry.
2. Nozzle size and position relative to throat.
3. Flow exit velocity.

4. Swirl.

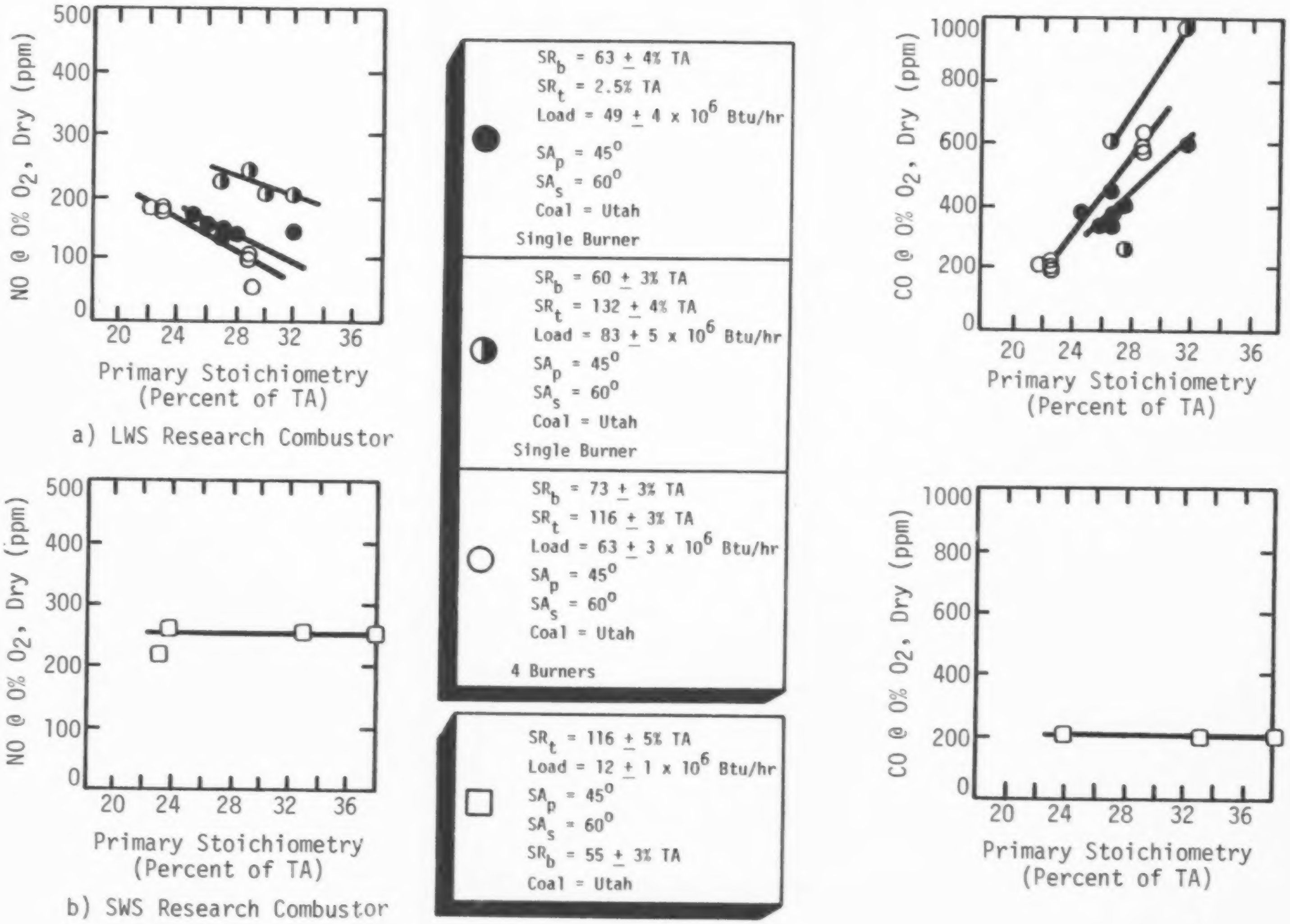
Of the above variables, only the fuel nozzle size was not explicitly studied; however, over the practical range, this variable (at constant velocity) is considered to have only a secondary effect on emissions and performance.

Short Flame DMB Designs

Primary Stoichiometry and Velocity

In practice, primary stoichiometry at full load is dictated by the pulverizer requirements and coal properties. Additionally, as load is decreased primary stoichiometry increases due to standard commercial pulverized operation and transport characteristics which necessitate nearly constant pulverizer airflow rates. Since commercial burners typically operate at fixed burner settings over the entire load range and with fixed geometry, then varying primary stoichiometry will also result in changes in the primary velocity. (It should be noted that if overall stoichiometry is maintained, then some reduction in secondary air velocities will also occur.) The combined effects on burner operation could result in changing the fuel/air mixing rates sufficiently that the flame characteristics could change from a short flame with ignition close to the burner exit to a long diffusion flame with ignition further away from the burner exit. These types of variations can impact NO, CO and flame stability characteristics. Since field operating experience has demonstrated that NO_x levels decrease as load is decreased, then from a design standpoint, the burner should be designed to provide (1) a stabilized flame near the exit with minimum NO_x levels at full load, and (2) flame stability over the entire load range. Therefore, the experimental effort first concentrated on establishing the impact of primary stoichiometry at full load with fixed fuel nozzle diameter designs, and then on changing burner parameters such as primary and secondary swirl angle. Load was not expressly varied since the required excess air and primary-air-to-coal ratio are strongly dependent on the site operating specifications and firing equipment.

Typical results for the three single secondary burners and the four-burner configuration are presented in Figure 4-10. The data presented for each burner were obtained at constant load, overall stoichiometry and burner



a) LWS Research Combustor

b) SWS Research Combustor

Figure 4-10. Effect of Primary Stoichiometry on NO/CO Characteristics for Single Secondary Burner(s).

zone stoichiometry. In Figure 4-10a the results obtained in the large Watertube Simulator (LWS) are presented, and in Figure 4-10b the results are presented which were obtained in the Small Watertube Simulator (SWS). For the burners tested in the LWS, all resulted in increasing the NO and decreasing CO as the primary stoichiometry was lowered. (As discussed later, these characteristics are completely opposite to that associated with changes in the stoichiometry at the burner throat.) Although not explicitly shown in Figure 4-10, increasing the primary stoichiometry did result in increasing the flame length; however, for these burners, over the range tested, the flame was still controlled by a weak internal recirculation zone and did not approach the long diffusion Type A flame. This would suggest that the effects measured on NO and CO are dominated by the changes in aerodynamics primarily altering the ignition characteristics. This hypothesis is further supported by consideration of the results obtained in the SWS where the firing wall and floor are refractory lined providing high temperature radiating sources, and due to confinement, increased high temperature recirculation near the burner and flame front. All of these factors should enhance the ignition characteristics. Note in Figure 4-10b that over the same range in primary stoichiometry as that of 4-10a and at similar burner zone stoichiometries, both the NO and CO are unchanged. These results suggest that if the burner is designed to operate with the desirable flame characteristics at full load, then the design primary stoichiometry will not be an important NO_x design parameter.

Since stability is dependent on factors other than the burner alone (e.g., fuel grade, firing equipment, etc.), it is difficult in a limited effort to generate sufficient information to specify general design criteria. The results do suggest, however, that stability can be attained by proper matching of the primary/secondary velocities (axial and swirl) to produce the desired flame characteristics even at low burner zone stoichiometry.

Primary Air Swirl

The primary air swirl can be used to promote more rapid mixing and dispersion of the coal and volatiles within the burner firing zone. Primary air swirl should, therefore, affect both the NO_x and performance characteristics. Since rapid mixing which provides essentially plug flow at the burner throat should result in the highest level of NO_x, then the design goal should be to define the best trade-off between the mixing rate and the desirable ignition characteristics. To evauate this parameter, experiments were conducted for several values of primary air swirl over a range in overall excess air, keeping all primary and secondary flow parameters and secondary swirl settings constant. The most extensive effort was conducted using the 50 x 10^6 Btu/hr single secondary burner in the LWS, wherein primary swirl was varied from 0^0 (100 percent axial flow) to 60^0 using the device depicted in Figure 4-6. Typical NO and CO results are shown in Figure 4-11. (Although not shown, when the swirl angle was set at 0^0 it was not possible to obtain acceptable flame stability.) As shown in Figure 4-11, at 30^0 swirl angle an acceptable flame was achieved with minimum emissions, and no measurable increase in NO_x was observed when the swirl angle was increased to 45^0. Further, increasing the swirl angle to 60^0 resulted in a large increase in NO_x. Due to the limited range and scatter in the CO data, the effect of swirl angle on CO is unclear. The indicated lines represent a best judgment as to interpretation of the results. This interpretation would indicate that both the fuel/air mixing characteristics and ignition flame characteristics are changing significantly. Therefore, there should be a design trade-off between NO and CO with primary swirl and lower swirl angles providing lower NO_x levels. Ignition stability represents the lower limit of operation, although it would not be prudent to design at that low a level. Since ignition stability plays a key role in the ability to minimize both NO and CO, the specific design point for primary swirl will depend on the site-dependent parameters.

Coal Nozzle Setback

Adjustment of the coal nozzle location with respect to the burner throat allows for rapid variations in the mixing characteristics upstream of the burner throat. As mentioned above, this can provide a trade-off between the ability to obtain improved stability characteristics and NO_x. Using the 12.5 x 10^6 Btu/hr single secondary burner, the nozzle location relative to the throat was varied from zero to 3.5 inches aft of the throat location. The NO results presented in Figure 4-12 are indeed encouraging

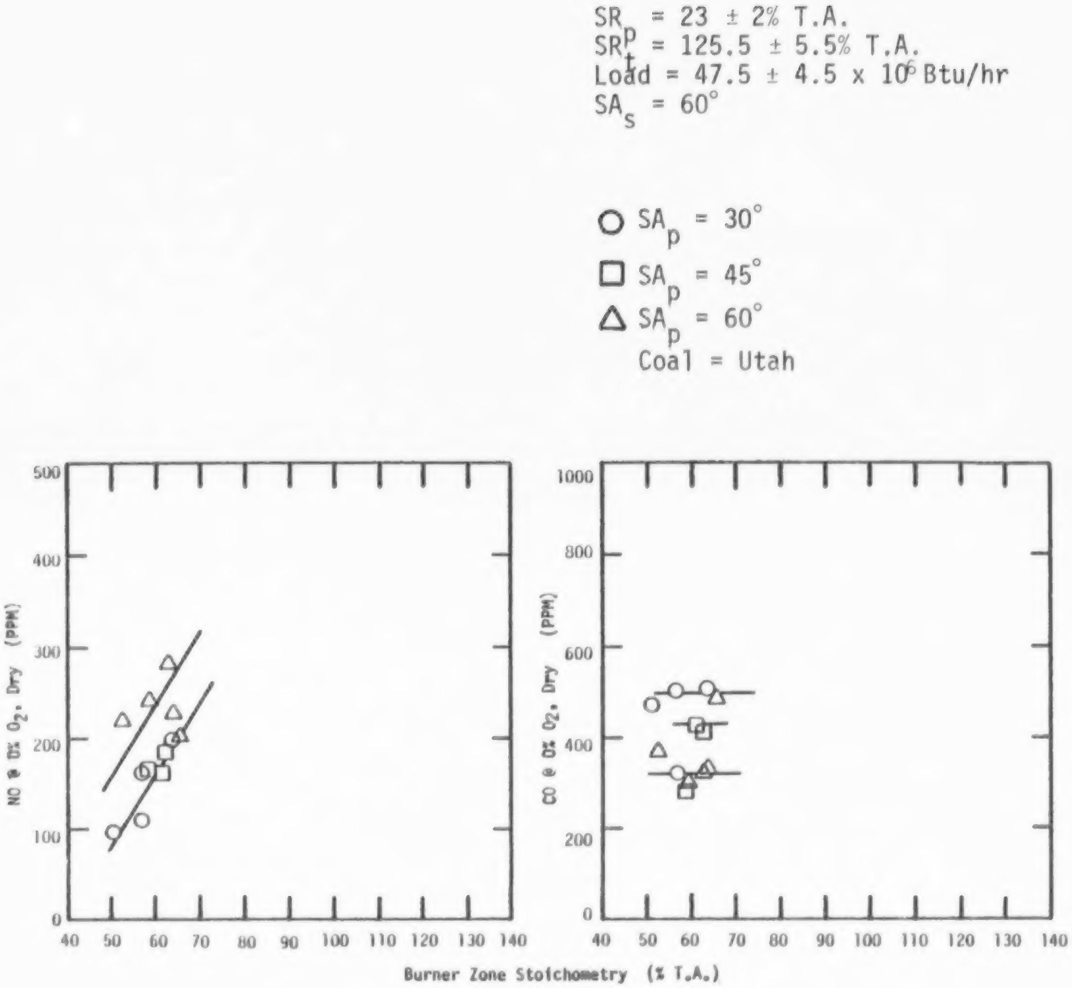


Figure 4-11. Effect of Primary Swirl Angle on NO and CO Using the 50 x 10^6 Btu/hr Single Secondary Burner.

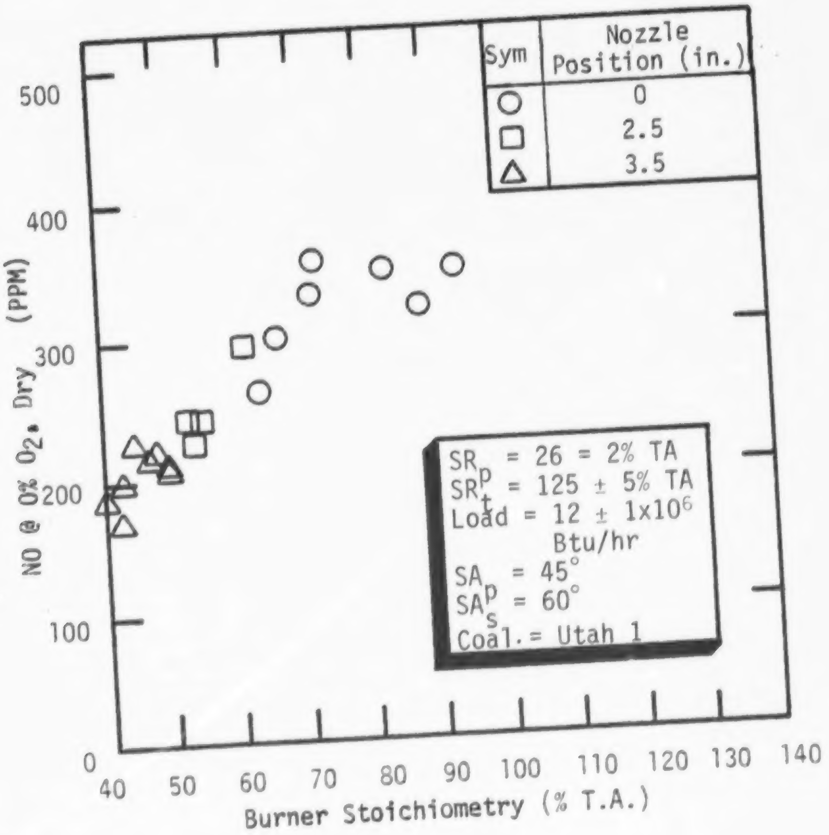


Figure 4-12. Effect of Primary Nozzle Setback on NO_x Emissions (12.5 x 10^6 Btu/hr Single Secondary Burners).

in that NO emissions appear to be insensitive to nozzle setback when burner zone stoichiometry is held constant. Although not explicitly shown on this figure, lower values of burner zone stoichiometry were achievable while maintaining excellent flame stability characteristics as the nozzle setback was increased.

Long Flame DMB Designs

During the early phases of the program, a new commercial pulverizer was purchased and installed in the LWS system. The new pulverizer required a significant change in the air necessary for proper pulverizer operation resulting in a significant increase in the primary coal nozzle injection velocity. This change in primary velocity resulted in a large difference in the stable operating limits of the burner. An example is shown in Figure 4-13, wherein the high primary velocity the burner could be operated at a burner zone stoichiometry only as low as 90 percent of theoretical air, while for the lower velocity, stable operation could be maintained at values as low as 60 percent of theoretical air. Also of interest is that equivalent NO levels were attained at differing overall burner zone stoichiometry, supporting the contention that the slower diffusion rate results in a lower "effective" stoichiometry in the combustion region.

These results suggest that the longer the design flame, the more sensitive the burner will be to stability. The specific design value will depend on the overall boiler duty cycle requirements and pulverizer requirements since these variables set the limits of operation. The burner zone stoichiometry will be defined to meet the NO_x goals at full-load operation and the primary velocity should be set for stable operation over the load range. (Lowering load results in increasing primary nozzle velocity and increasing burner zone stoichiometry.)

4.1.2.2 Air System Variables

The DMB utilizes both secondary air passages and tertiary air ports. Physical separation of the tertiary air from the burner air ensures that the burner zone will operate overall at substoichiometric conditions and final staging is then controlled by interaction with the outboard tertiary air. The ability to evaluate the effect of tertiary air independent of the

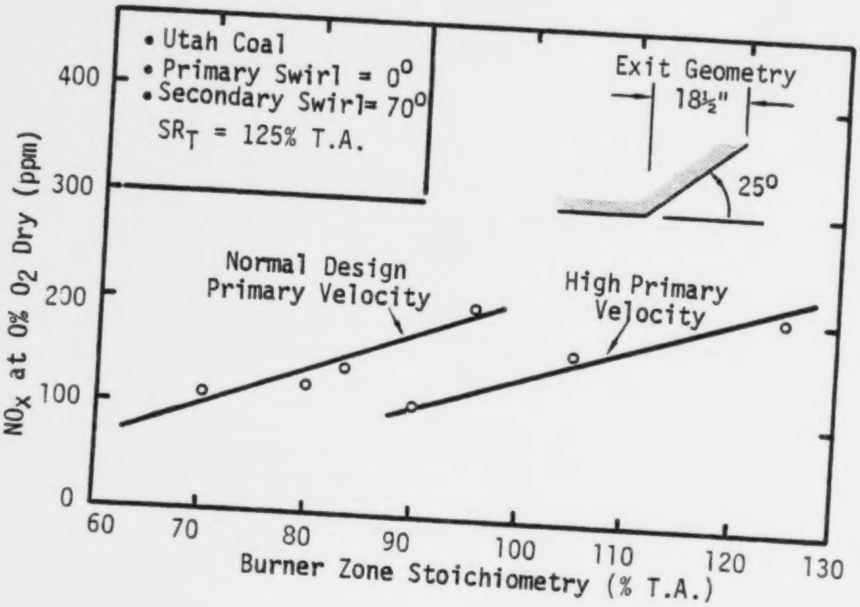
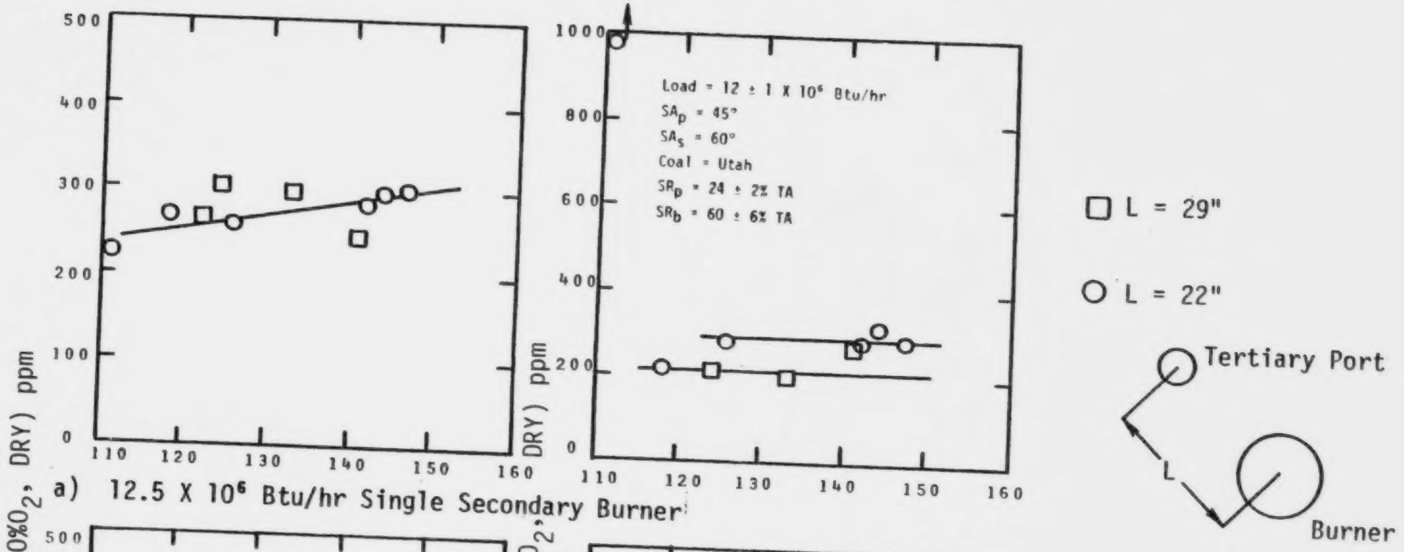


Figure 4-13. Effect of Primary Air Velocity on Operating Limits for 50 x 10^6 Btu/hr Dual Secondary Burner.

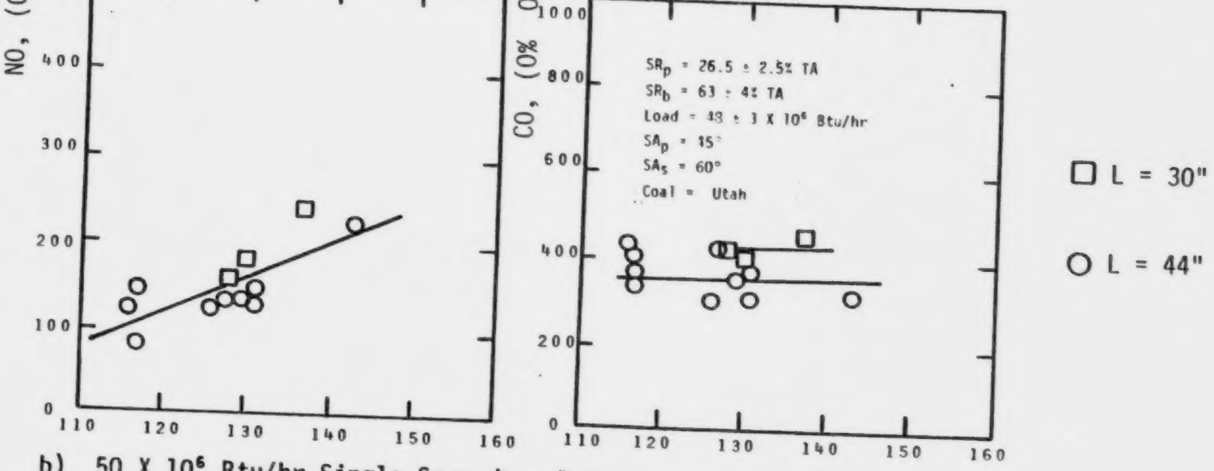
secondary air is not possible with fixed burner geometry. That is, if the overall excess air remains constant, then changing the secondary airflow rate results in variations in (1) burner zone stoichiometry, (2) secondary air velocities, and (3) tertiary air velocity. Consequently, changing secondary air can affect the mean stoichiometry in the burner throat, burner fuel/air mixing rates, flame characteristics and staged air mixing characteristics. While physical separation of the parameters is not completely possible, sufficient parameters, both flow and geometric, were varied to heuristically deduce gross mechanisms. The tertiary air parameters were only varied using the short flame DMB designs.

Tertiary Air Variables

Variations in tertiary air port location and injection velocity were evaluated with both the single and four-burner configurations and jet velocity was evaluated in two single burners. The impact on NO and CO characteristics was studied at two tertiary port locations using the 12.5 and 50 x 10^6 Btu/hr burners. The results shown in Figure 4-14 show that for both burner sizes the port locations affected CO levels, while NO appeared unaffected. Of particular interest is that changing the overall stoichiometry (as well as tertiary air injection velocity) at a fixed tertiary port location has little effect on the CO characteristics. This suggests that the overall mixing between the burner fuel/air products is insensitive to the tertiary air velocity while physically moving the ports closer affects only the overall mixing. Since the injection velocity decreases rapidly with distance from the nozzle, it is possible that the changes in effective shear mixing between the burner zone products and the tertiary jets is not significant over the practical range evaluated. The above results relative to the impact of tertiary air velocity on mixing characteristics are further supported in Figure 4-15, wherein tertiary jet velocity was varied independently using the 12.5 x 10^6 Btu/hr single and multiburners. Note that in both cases, variation in velocity by as much as a factor of two did not affect NO characteristics in either burner. A complete set of data were available from the four-burner tests, and they show that CO was also constant.



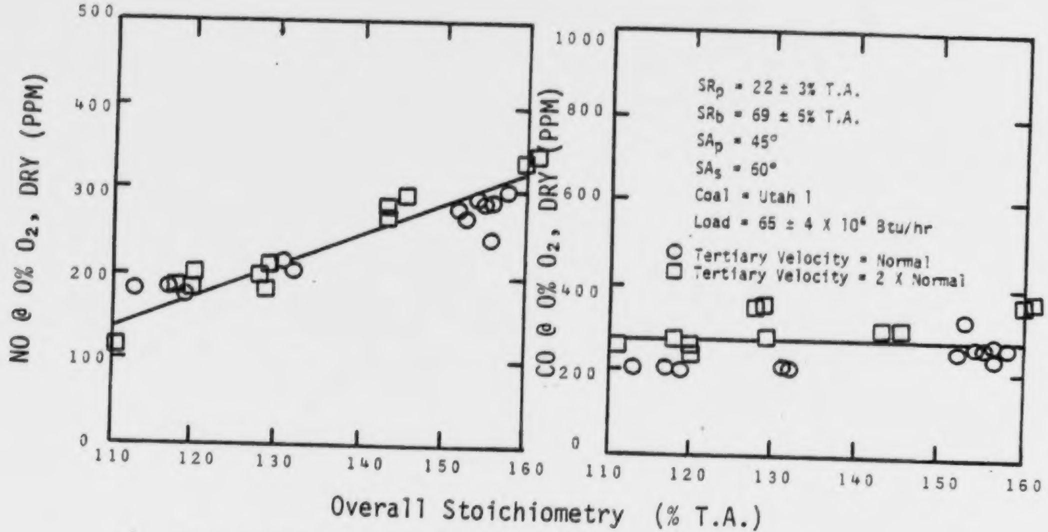
a) 12.5 X 10^6 Btu/hr Single Secondary Burner



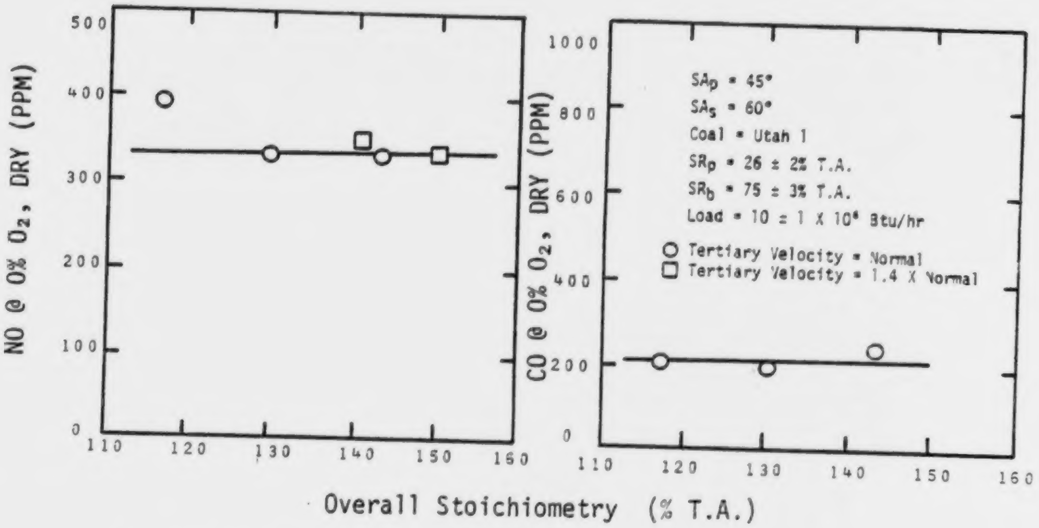
b) 50 X 10^6 Btu/hr Single Secondary Burner

Overall Stoichiometry (% T.A.)

Figure 4-14. Effect of Tertiary Port Location on NO & CO Characteristics.



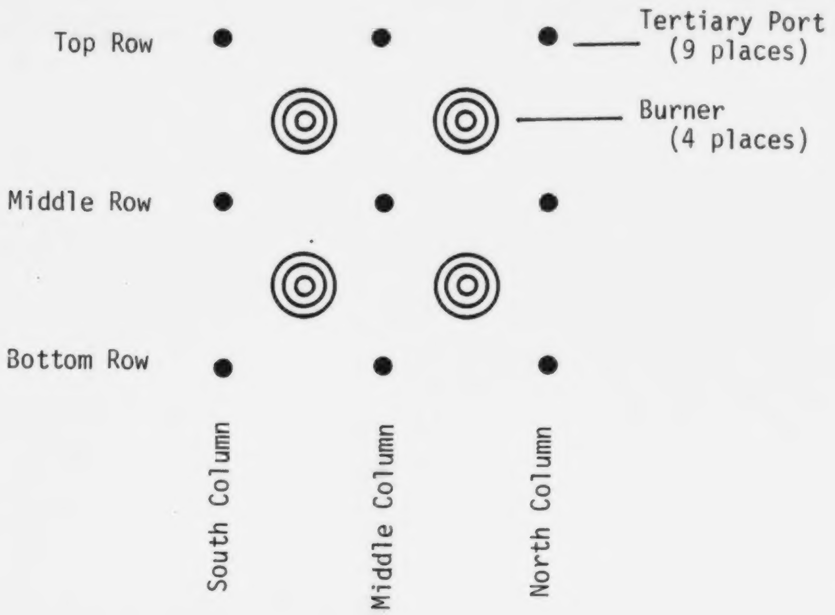
a) Four Single Secondary 12.5 X 10^6 Btu/hr Burners



b) Single Burner - 12.5 X 10^6 Btu/hr Single Secondary Burner

Figure 4-15. Effect of Tertiary Air Velocity on NO and CO Characteristics.

The effect of tertiary air port location was also studied in the four-burner multiburner configuration shown in the sketch below.



Tests were conducted with various rows and/or columns out-of-service to define the sensitivity of NO and CO, on number and location of the tertiary ports. The results presented in Figure 4-16 again show that within experimental accuracy the NO characteristics were completely unaffected by the variations in tertiary air velocity or tertiary port location. The general conclusion from this is that for these short Type B flames the burner zone is essentially premixed and burns at the burner zone stoichiometry, and therefore, NO is formed in the burner flame zone before substantial interaction with the tertiary air. It is not known, however, if this will hold for large burner configurations, although the aerodynamics should be scalable for long Type A flames wherein the diffusion of the fuel into the air is delayed. While NO was not affected by tertiary port location in the multi-burner configuration, the variations in CO were dramatic. Note that any change in tertiary ports out-of-service were accompanied by an increase in CO. This result reveals that the tertiary port location relative to the burners has a strong impact on the overall mixing in the lower furnace, and that improper port location will result in incomplete CO burnout in the high temperature region of the furnace.

SSB - 12.5 x 4 Closed Tertiary Analysis

○ Baseline (all ports open)
□ Bottom Row Closed
△ Middle Row Closed
◇ Middle Row & Column Closed
⬡ South Column Closed
▽ North Column Closed
0 Middle Column Closed

SR_p = 21 ± 2% T.A.
SR_b = 62 ± 5% T.A.
Load = 67 ± 5 x 10^6 Btu/hr
SA_p = 45
SA_s = 60
Coal = Utah 1

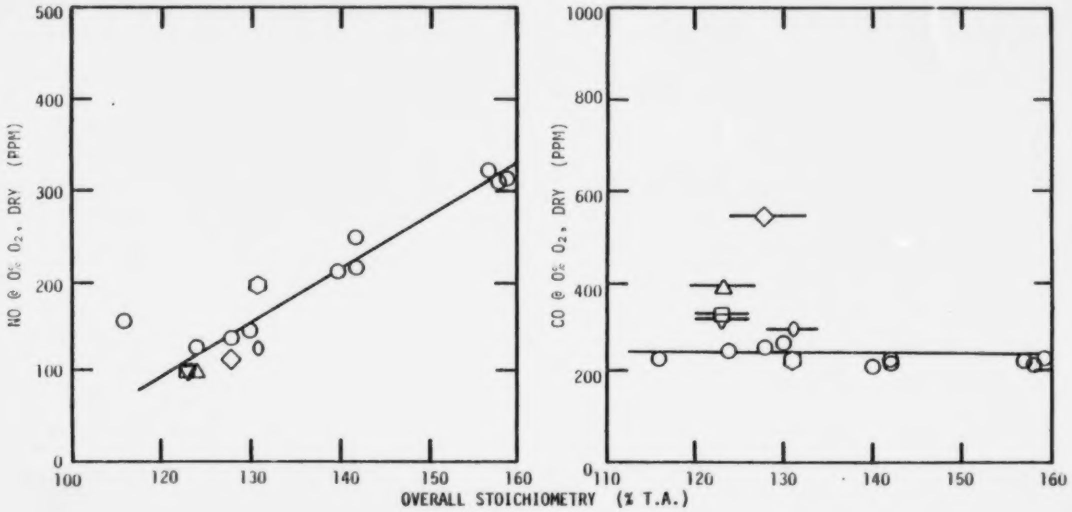


Figure 4-16. Effect of Tertiary Port Location and Number on NO/CO Characteristics in a Multiburner Configuration.

Secondary Air Variables

Secondary air was varied in order to control the burner stoichiometry and the fuel/air mixing rates at the burner throat (burner zone stoichiometry). Interacting parameters precluded the ability to study these independently, since variation in burner zone stoichiometry also result in changes in secondary air velocity. Further, if the overall excess air remains constant, lowering the burner air results in an increase in the tertiary air. Based on the result discussed above, however, the effect of increasing or decreasing the tertiary airflow on NO/CO was found to be negligible. Therefore, for the DMB evaluated, it is expected that NO and CO variations with secondary airflow rate can be attributed to (1) the overall burner zone stoichiometry, (2) fuel/air mixing rates, and (3) flame characteristics, independent of tertiary air characteristics.

While burner zone stoichiometry was studied using all of the burners described above, the results were similar to that shown for the 50 x 10^6 Btu/hr single secondary burner in the upper plot of Figure 4-17. All burner results, regardless of overall excess air, show that lowering the burner zone stoichiometry results in a decrease in NO. The reduction in NO is accompanied by no increase in CO until the primary/secondary flows can no longer provide adequate mixing and flame characteristics, wherein the CO then rapidly increases. While the flame is still stable initially, continued reduction in burner air eventually leads to instability and flameout. In comparing the CO and NO characterisitics, note that the impact of burner zone stiochiometry on NO remains unchanged even as the CO markedly increases. This suggests that the NO formation is being controlled principally by the burner zone stoichiometry and not by the primary/secondary flow mixing rates. The conditions producing the increase in CO shown in Figure 4-17 were found to be strongly dependent on the burner settings, as well as design velocity. In fact, at full load it was possible to obtain minimum CO and NO over a wide range in excess air levels by simply varying both burner zone stoichiometry and swirl conditions. However, in a field installation, it may not be feasible to adjust these parameters as boiler and firing conditions change. An example of varying the secondary swirl is shown in Figure 4-18. Although not shown on the figure, at zero swirl the flame could not be stabilized, even at high burner zone stoichiometry, and resulted in flame-out. As secondary swirl was increased to 30^0, it was possible to achieve

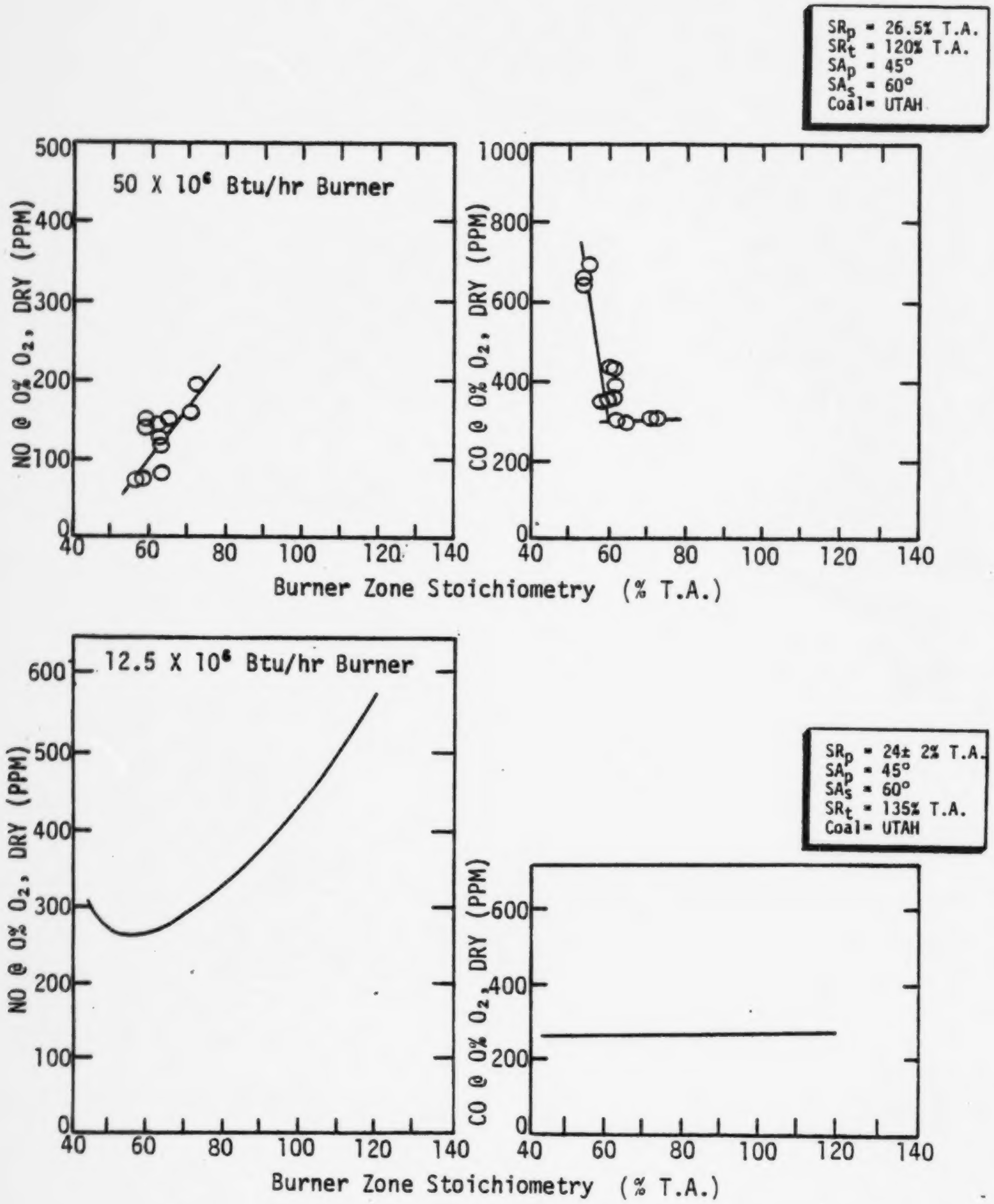


Figure 4-17. Effect of Burner Zone Stoichiometry on NO and CO Emissions with Two Single Secondary Short Flame Burners.

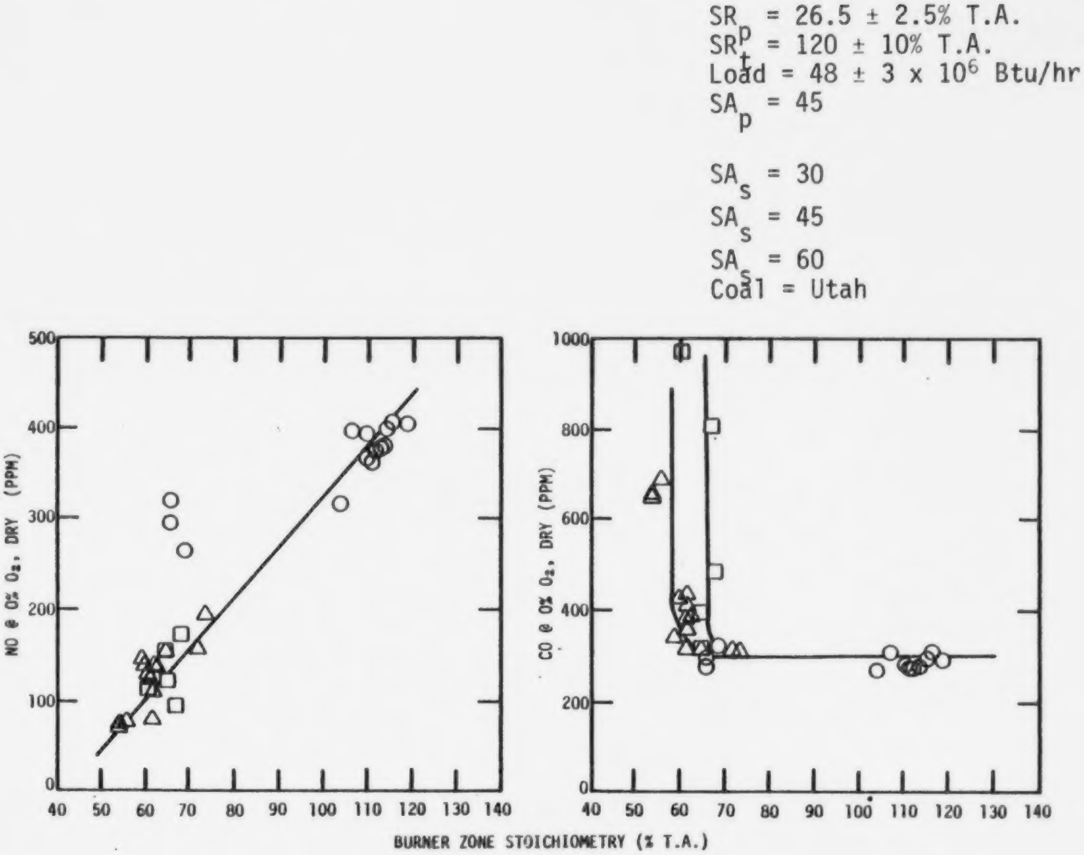


Figure 4-18. Effect of Secondary Swirl Angle on NO and CO Characteristics (50×10^6 Btu/hr Single Secondary Burner).

a stable flame over burner zone stoichiometry of about 70 to essentially unstaged conditions of 120 percent of theoretical air. Lower burner zone stoichiometries were possible as the secondary swirl angle was increased. Note that the NO characteristics were essentially unchanged with secondary swirl angles, while the burner efficiency (CO) was improved by increasing secondary swirl.

The results shown for the 12.5 x 10^6 Btu/hr burner (the lower plot of Figure 4-17 support the thesis that for the short flame burners, the burner zone acts as a well mixed first stage system. These results represent a cross plot of data obtained at various burner zone stoichiometries over a range of excess air levels. As shown, the NO decreases as burner zone stoichiometry is decreased until a minimum is reached and then with further decreases in stoichiometry, NO increases. These results are very similar to those found in small-scale testing with plug flow reactors wherein the staging was well controlled. It is felt that for the larger burners, a minimum would also occur if burner zone were lowered beyond that evaluated (≈40% T.A.). However, this would be very difficult since at 40%T.A., the air flow rate through the secondary air passages is only 1/5 of the unstaged value.

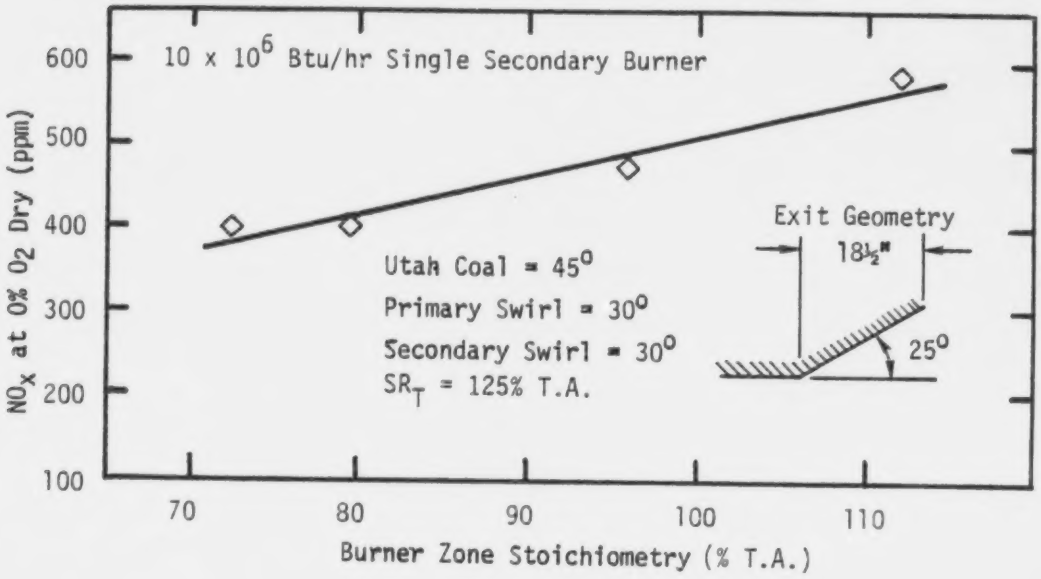
Long Flame DMB Designs

The burner zone stoichiometry was varied identically to that described for the previous burners. Typical results for the two scales of burners are provided in Figure 4-19. The sensitivity of NO to the burner zone stoichiometry is approximately the same as that of the shorter flame burners discussed previously. Although for the same burner capacity, the longer flame will achieve NO levels equal to the short flame design only at higher overall burner zone stoichiometry. This could be the result of higher mean temperatures with the short flame or higher O_2 concentrations during devolatilization. The specific burner zone stoichiometry design point will depend on the boiler and coal characteristics, as well as the desirability of providing a long or a short flame.

4.1.2.3 Burner Exit Geometry

All of the development DMB designs utilized cast refractory exists. The effects of burner exit geometry on NO emissions were evaluated on the long flame DMB designs.

Two differing burner exit scaling methods were evaluated: (1) direct geometric scaling wherein the quarl length was extended, keeping the divergence angle constant; and (2) a combination of increasing the divergence angle and shortening the quarl length. In the geometric scaling case, extending the quarl



Primary Air at Normal Design Velocity

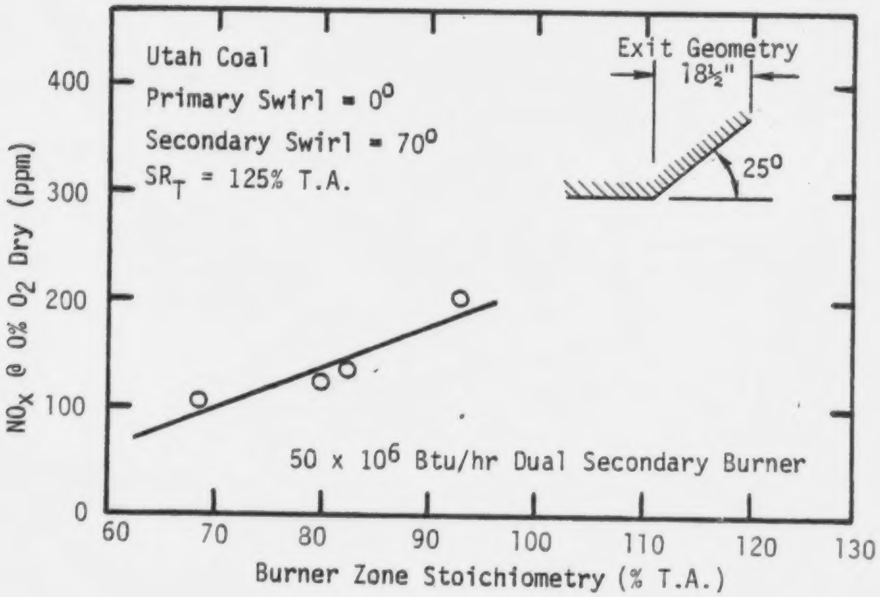


Figure 4-19. Effect of Burner Zone Stoichiometry on NO Characteristics for Long Flame Burners.

should cause the flow to expand to more nearly fill the exit, resulting in more rapid mixing of burner fuel/air and shortening of the flame length. The results, obtained using the 10 x 10^6 Btu/hr burner presented in the upper plot of Figure 4-20, show that extending the quarl significantly increased the NO levels suggesting more rapid fuel/air mixing. In addition, the longer quarl length resulted in significantly improved stability characteristics. The quarl geometry which resulted in the best stability characteristics was also evaluated at the 50 x 10^6 Btu/hr burner scale. The large burner was stable over the operating range shown in the lower plot of Figure 4-20, even at the high primary air velocities. Since typical commercial systems utilize quarl lengths considerably shorter than 18.5 inches, an attempt was made to try to obtain equivalent flame characteristics by both shortening the quarl length and increasing the quarl angle. With this configuration, although the NO levels were similar to the 25° x 18.5 inch quarl as shown in Figure 4-20, the stability characteristics were not acceptable.

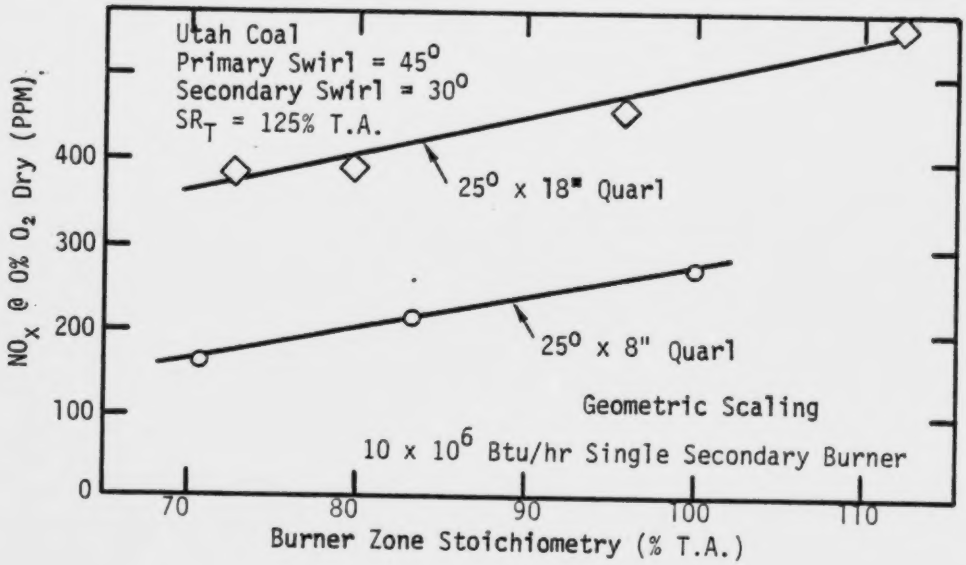
These results suggest that for stability control, a long flame burner design operating at low burner zone stoichiometries may require a longer quarl length than is normally utilized in commercial practice. This requirement could significantly limit retrofit of long flame systems in existing boilers.

4.1.3 Evaluation of Operating Variables

For the purpose of this report, operating variables will be defined as those which are normally varied during typical burner operations in a boiler. They include:

- Overall excess air
- Burner heat release (load)
- Primary and secondary temperatures

In the burner development effort overall excess air was varied, keeping the burner operating conditions constant by adjusting the tertiary airflow rate. Although this results in changing both the overall excess air and tertiary air injection velocity, it was determined that this latter parameter did not influence the NO characteristics (see Section 3). Therefore, NO variations with excess air are likely to principally be the result of changes in conversion of the available XN species emerging from the burner zone, as well as any thermal NO contribution. The variations in CO, without varying the burner stability, should be related to changes in overall mixing uniformity.



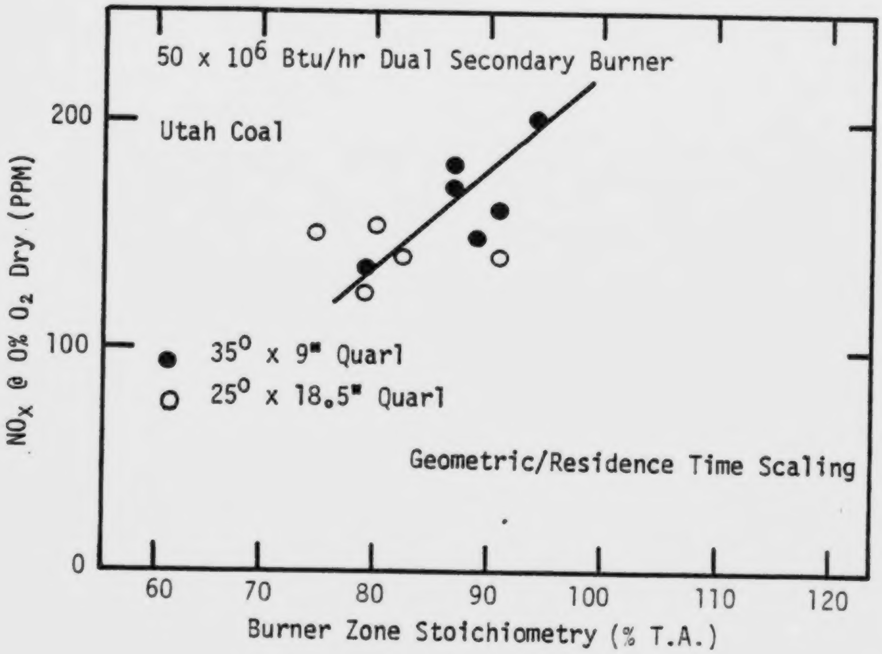


Figure 4-20. Effect of Quarl Geometry on NO Characteristics.

An objective of the DMB development was to establish sufficient single and multiburner scaling criteria so that large and small capacity burners could be designed to provide identical fuel/air mixing characteristics. Therefore, for a fixed furnace configuration, NO_x would not be sensitive to burner capacity. Another objective was by varying the furnace volume to establish the impact of the burner heat release rate on NO_x independent of burner scale. These two physical changes provide information to assess the range of application of the DMB technology to existing and future boilers.

4.1.3.1 Short Flame Designs

Overall Excess Air

The effect of overall stoichiometry on NO characteristics for all single secondary short flame burners evaluated are shown in Figure 4-21. Note that the single and multiple burners behaved similarly in that increasing overall excess air results in increasing levels of NO. It is interesting that comparing the two single burners evaluated in the LWS, the 50×10^6 Btu/hr burner NO characteristics appear to be more sensitive to excess air than the 100×10^6 Btu/hr burners, suggesting that there might be a scale effect on the rate of mixing of the tertiary air with the burner air. The corresponding CO characteristics are shown in Figure 4-22. While the minimum levels achievable are dependent on the characteristics of the specific burner and can be changed by varying burner settings, the overall trends are identical. At high values of excess air the CO minimizes as would be expected. Decreasing excess air over a broad range in excess air does not influence CO until the overall mixing characteristics and flame characteristics of the burner become affected. At this point there is insufficient oxygen available to fully oxidize the carbon in the fuel and CO emissions increase rapidly. This same behavior has been observed with commercial burners operating in steam generators. However, the CO levels at high excess air are generally much lower. The higher CO levels in the EER research furnaces are believed to be a result of the cold furnace designs (low heat release per unit volume and per unit cooled surface area).

These results clearly show that the DMB should be operated at the lowest possible excess air commensurate with satisfactory CO and/or carbon burnout. This will minimize NO emissions and/or allow the burner to be operated at higher burner zone stoichiometries achieving the same NO level.

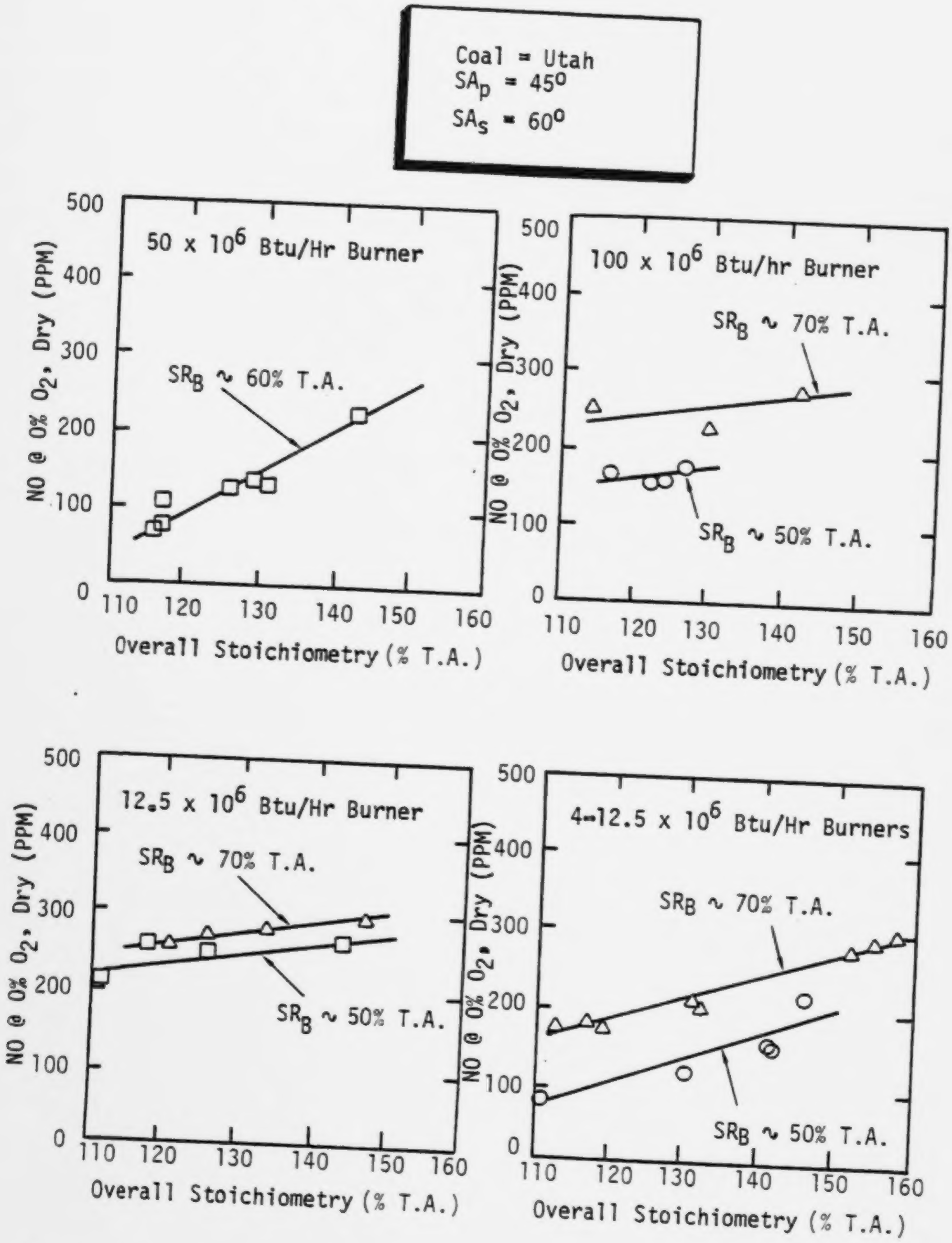


Figure 4-21. Effect of Overall Stoichiometry on NO Characteristics for all Single Secondary - Short Flame Burners.

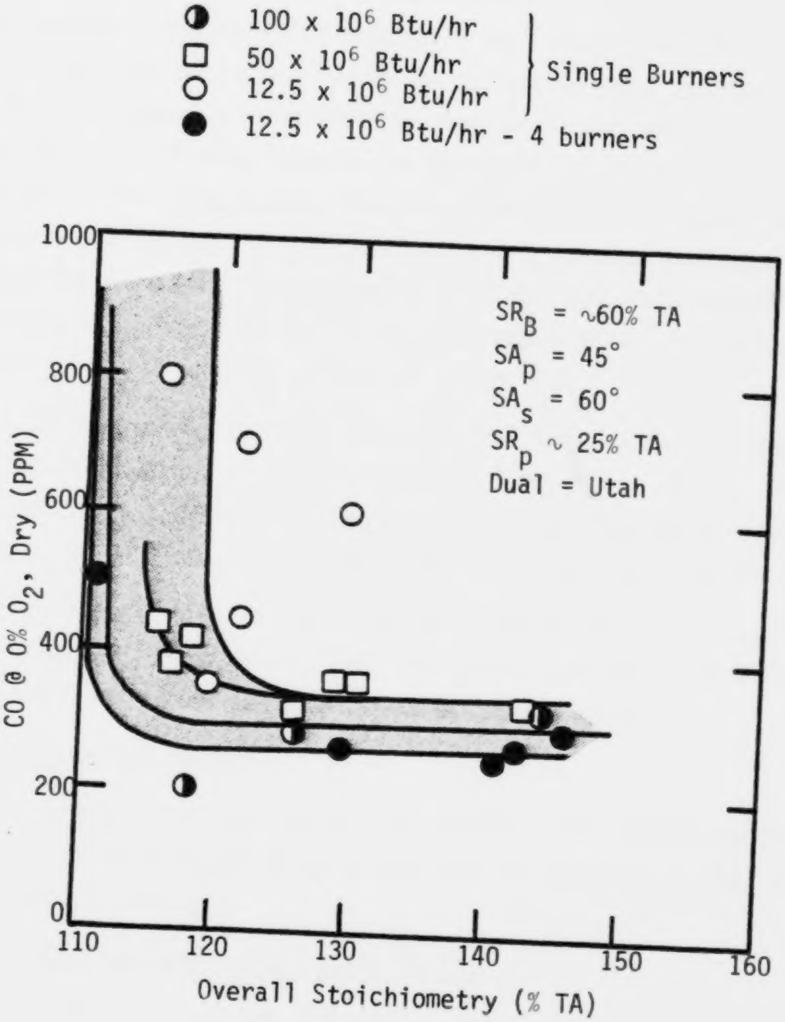


Figure 4-22. CO Characteristics as a Function of Overall Stoichiometry for the Single Secondary - Short Flame Burners.

Burner Heat Release

Figure 4-23 shows the relationship between NO emissions and burner heat release for the short flame DMB designs. These data were obtained over narrow ranges of operating conditions and are thus directly comparable. Although there is some scatter, the data for the three configurations tested in the LWS generally lie on a line of increasing NO emissions as heat release rate is increased. This increase in NO emissions rate as firing rate is increased has been observed in tests of many burners in research furnaces as well as field operating boilers. This phenomenon is due primarily to increased turbulent fuel/air mixing and a hotter furnace environment at higher firing rates. It should be noted that the LWS furnace has a cold thermal environment and that changes in firing rate over the factor of two ranges shown in Figure 4-24 would not be expected to significantly affect NO generation.

Figure 4-23 also shows data obtained in the SWS. Although these data do not cover a sufficient range of firing rates to identify a trend, they are considerably higher than the extrapolated trend of the LWS data. This is believed to be a consequence of the SWS furnace design (see Appendix B).

In summary, both burner firing rate and furnace design appear to influence NO emissions. However, it is clear that the burner designs tested allow satisfactory operation over a considerable range of firing rates.

4.1.3.2 Long Flame DMB Designs

Excess air characteristics for the 10 and 50 x 10^6 Btu/hr burners are shown in Figure 4-24. The NO dependence on excess air is similar to that presented for the short flame burners.

4.1.3.3 DMB Full-Load Operating Limits in LWS

The overall objective of the DMB effort is to define not only the impacts of burner design and flow parameters on NO/CO, but also to establish the potential for the DMB to achieve low NO_x values approaching 0.2 lbs/10^6 Btu. While the lower limit independent on the coal grade and burner/boiler configuration, it is still constructive to define the full-load operating limits as a comparison against other burners evaluated in the LWS using the baseline coal.

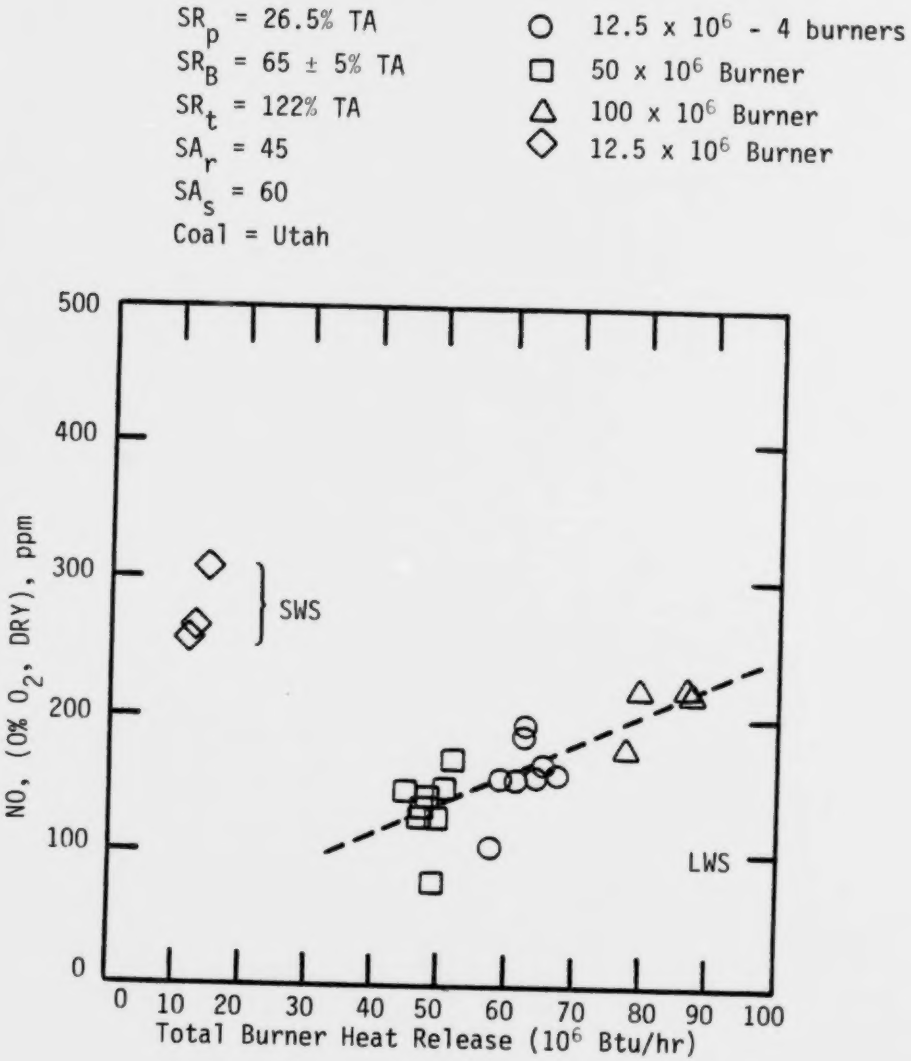
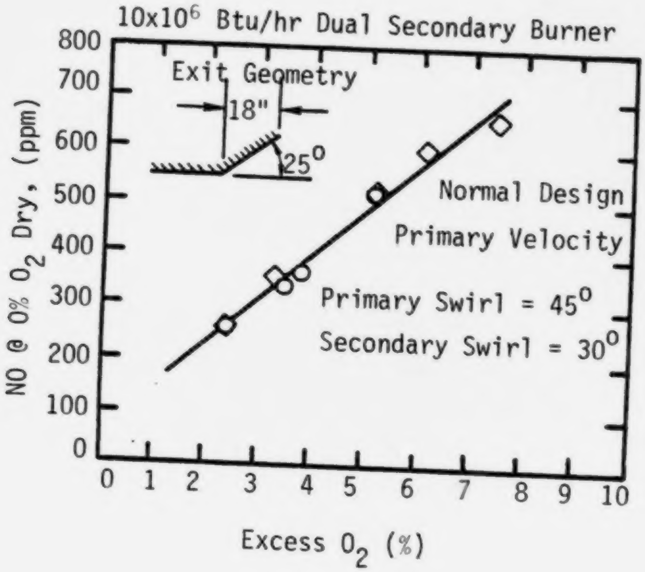


Figure 4-23. Effect of Burner Heat Release on NO Characteristics for the Single Secondary - Short Flame Burners.



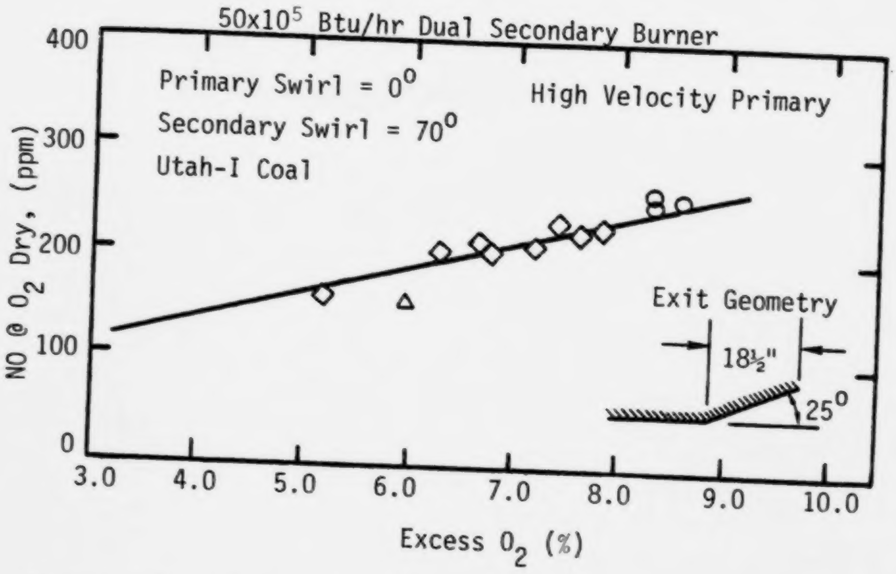
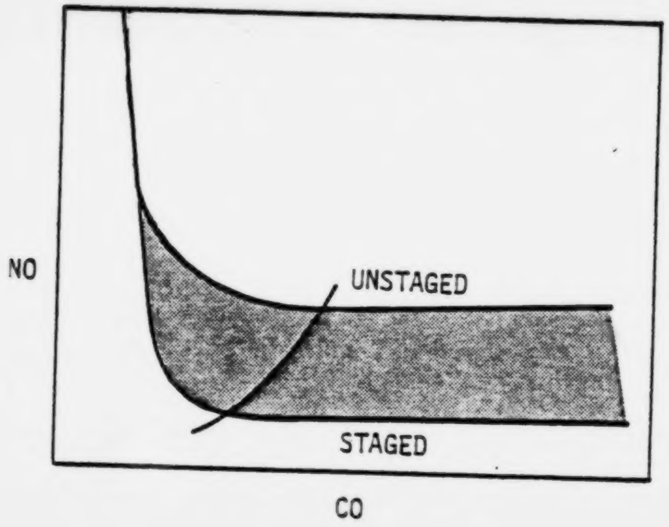


Figure 4-24. Effect of Excess Air on NO Characteristics - Long Flame Burner Designs.

In practice, a commercial burner is adjusted to provide the required flame shape and CO levels at full load and design excess air. The burner must then provide acceptable operation over the entire load and excess air ranges without further burner adjustments. When excess air is varied at full load, both NO and CO also vary with low excess air corresponding to low NO and high CO. This relationship between NO and CO can be plotted with excess air varying implicitly as shown on the unstaged curve in the sketch shown below.



The adjustment procedures for the DMB's tested in the research furnaces were similar to that described previously except that the adjustment of burner parameters and progressive staging allowed both CO and NO to be minimized. The improvement in performance is illustrated in the sketch above by the line joining the unstaged and staged curves. The lower staged curve represents the minimum NO for staged operations. Variations in NO and CO along this curve may be achieved by varying the burner adjustments and/or the degree of staging while maintaining the design point excess air at full load.

The results from all full load testing are shown on Figure 4-25 for the two 50×10^6 burners evaluated in the LWS combustor and the four-burner configuration as well as the single 100×10^6 Btu/hr burner results are presented in Figure 4-26. Note that the burner providing a long Type A flame achieved lower values of NO than the short Type B flame well-mixed burner. Direct comparison of the levels may, however, be unjustified as for the long flame burner some back wall impingement of the flame occurred. Therefore, the NO levels may be low and CO higher than would have occurred if impingement had not resulted.

4.1.4 Fuel Composition

4.1.4.1 Short Flame DMB Design

It is expected that the NO levels will be affected by fuel composition. The four fuels listed in Table 4-4 were tested in the LWS using the single 100×10^6 Btu/hr burner and the four 12.5×10^6 Btu/hr burners. In addition, a series of tests were also conducted in the SWS using the single 12.5×10^6 Btu/hr burners. The results presented in Figure 4-27 show that in the LWS furnace the Utah Nos. 1 and 2 and West Virginia coals all resulted in comparable NO levels when fired at the same overall stoichiometry. However, in the SWS furnace, while the West Virginia and Kentucky coals resulted in the same level of NO, the Utah No. 1 coal gave considerably lower NO values. Since these data are somewhat limited, it is not known whether the SWS fuel effects data are anomalous or the test conditions in the SWS emphasize the differences in fuel composition. Due to this uncertainty, future DMB designs should be tested with several coals to verify the effects of fuel composition.

4.1.4.2 Long Flame DMS Designs

The Utah and West Virginia coals were also tested in the 10×10^6 Btu/hr burner in the SWS. The results presented in Figure 4-28 show essentially no effect of fuel composition on NO. This is consistent with the majority of the short flame burner data and suggests that NO levels are similar for coals with approximately the same composition.

4.2 General DMB Design Requirements

The data presented in the previous sections have shown that distributed mixing burners can be designed and operated to produce a wide range of flame shapes and emission levels. This section summarizes these data and identifies the general requirements for distributed mixing burners designed for field boilers.

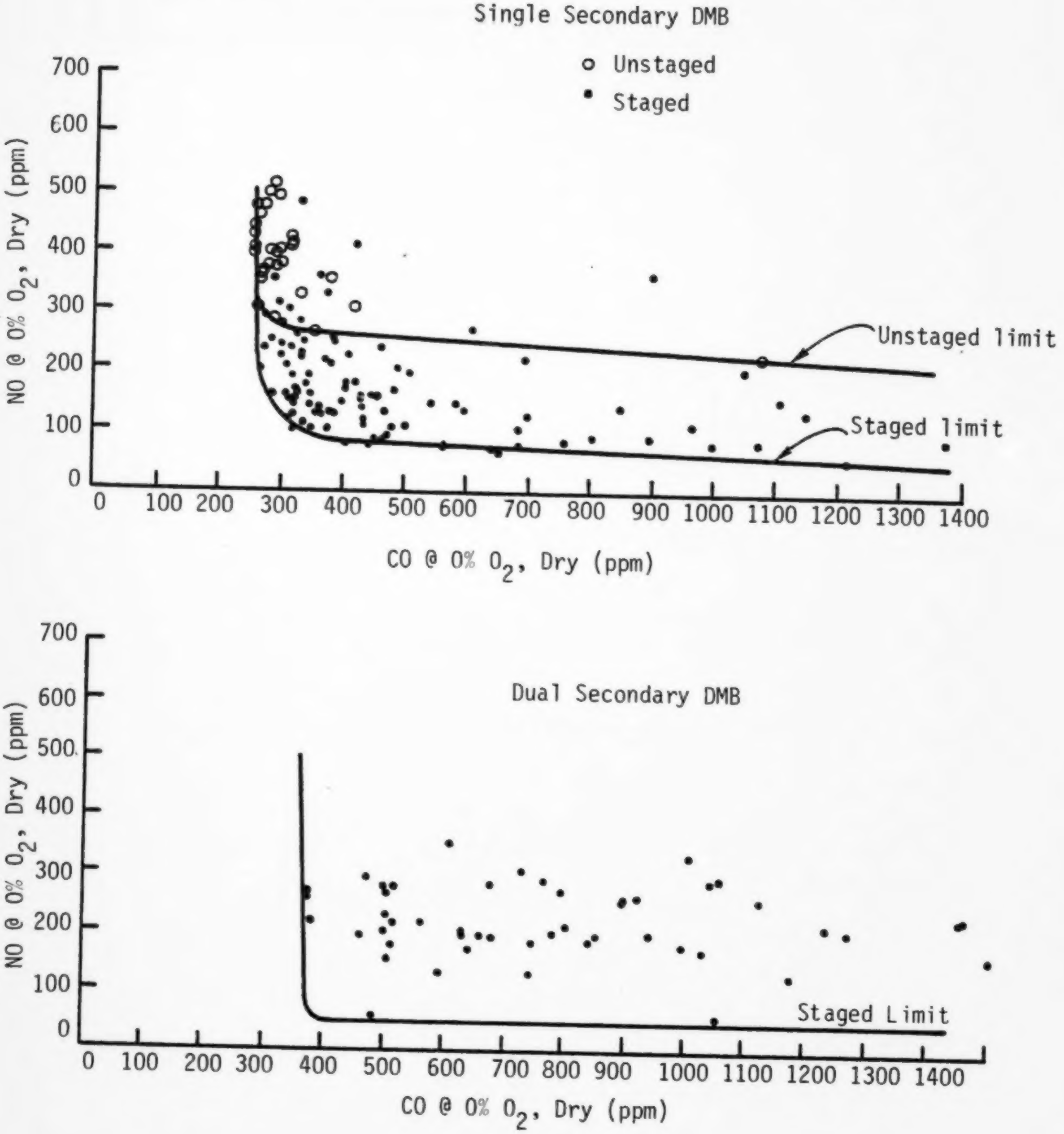


Figure 4-25. Comparison of Operating Limits for Two 50 x 10^6 Btu/hr Burners Having Distinctly Differing Flame Characteristics.

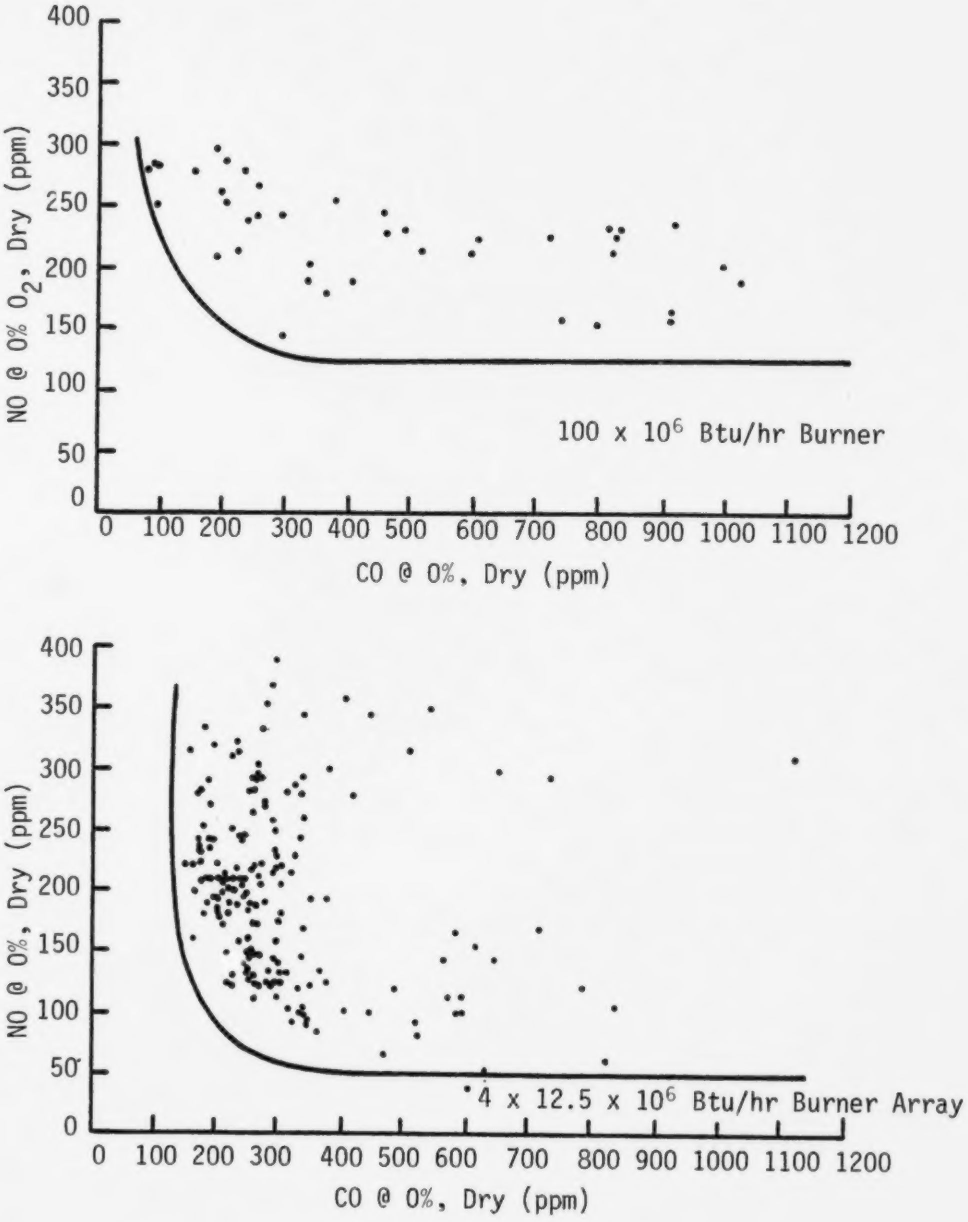


Figure 4-26. Operating Limits for a Single Large Capacity Burner and a Four Burner Array of Smaller Capacity Burners.

Table 4-4. Compositions of Coals Tested

Coal / Analysis	As Received				Dry Ash Free			
	Utah I	Utah II	West Virginia	Western Kentucky	Utah I	Utah II	West Virginia	Western Kentucky
Proximate, %								
Moisture	6.39	7.41	1.29	3.68	-	-	-	-
Volatiles	38.89	38.84	31.01	38.19	45.11	46.36	36.50	48.70
Ash	7.40	8.83	13.76	17.90	-	-	-	-
Fixed Carbon	47.32	44.92	53.94	40.23	54.89	53.64	63.50	51.30
Ultimate, %								
Carbon	68.49	66.89	71.44	60.83	79.45	79.86	83.92	77.57
Hydrogen	5.20	5.33	4.82	4.47	6.03	6.36	5.66	5.70
Nitrogen	1.33	1.43	1.32	1.28	1.56	1.71	1.55	1.63
Sulfur	0.64	0.70	1.75	2.98	0.74	0.84	2.06	3.80
Ash	7.40	8.83	13.58	17.90	-	-	-	-
Oxygen	10.64	9.41	5.80	8.86	12.34	11.23	6.81	11.30
Moisture	6.39	7.41	1.29	3.68	-	-	-	-
Heating value, Btu/lb	12,340	11.877	12,500	10,640	-	-	-	-

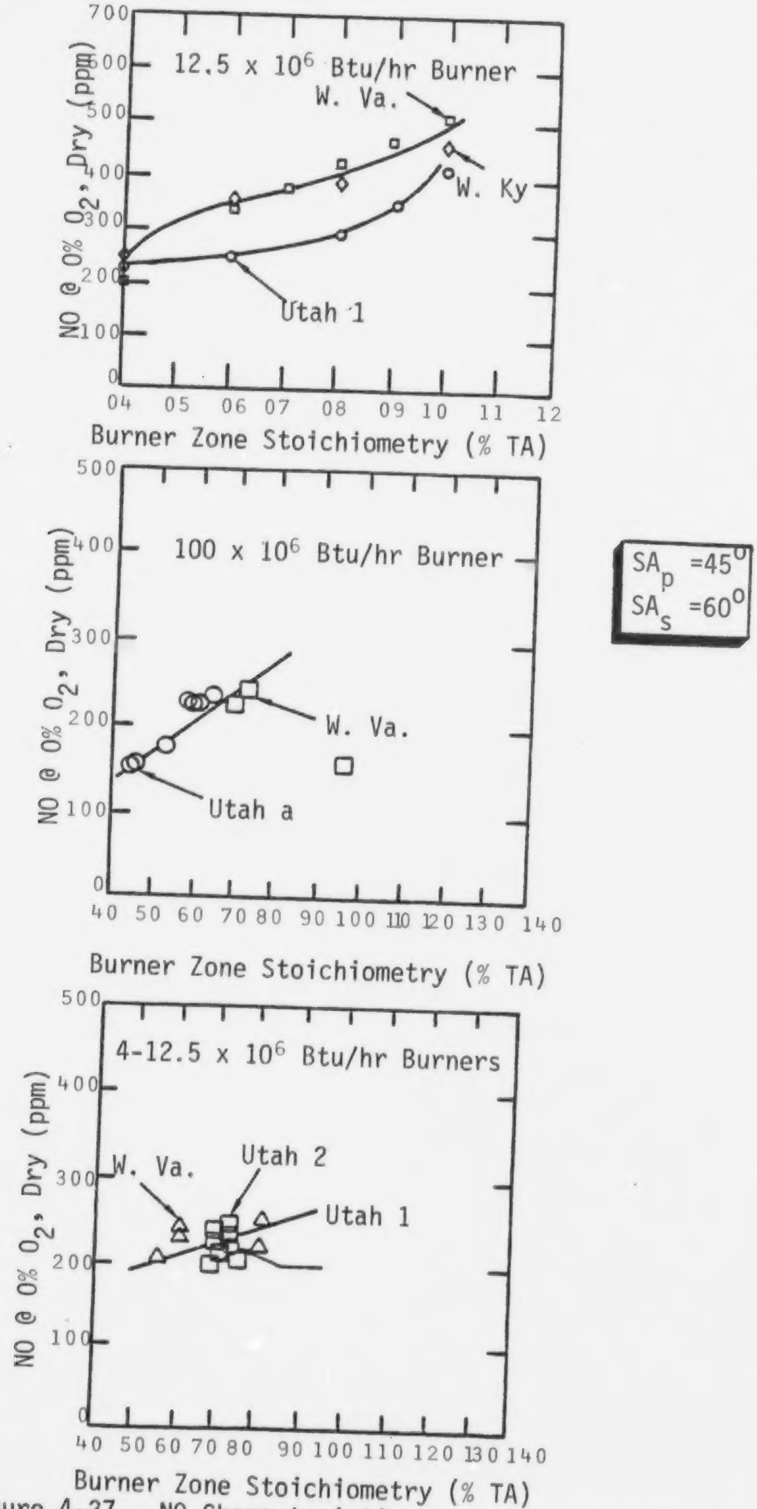


Figure 4-27. NO Characteristics with Differing Fuels for Short Flame Burners

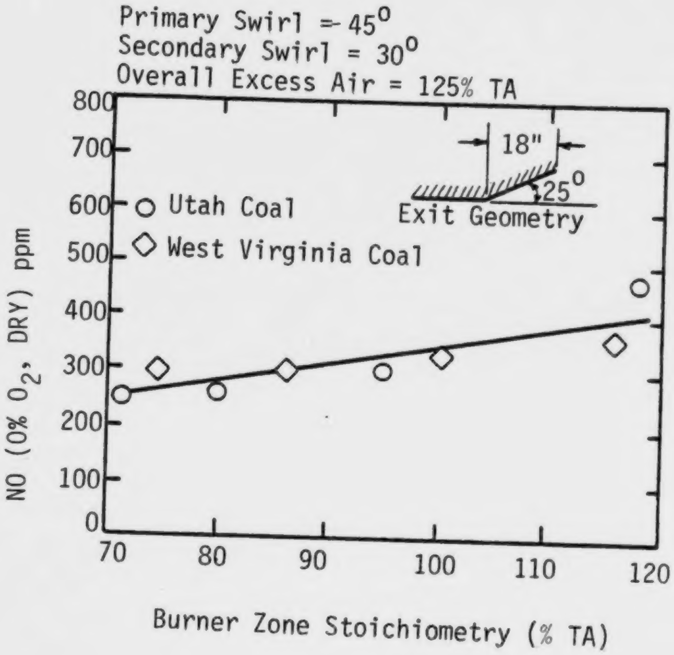


Figure 4-28. Effect of Fuel Type on NO_x Emissions for the 10 M Btu/hr Single Secondary - Long Flame Burner

The fuel system design has a significant influence on flame shape and length. Nozzles in which the coal and primary air are injected axially tend to produce slow fuel/air mixing and long Type A diffusion flames. Nozzles with impellers cause more rapid fuel/air mixing which tends to produce shorter, more compact, Type B flames. Long diffusion flames can be used in boilers with large furnace depths such as opposed wall-fired units. The NO emissions from this flame type were generally lower than those for short flames. Smaller furnaces, such as those in single wall-fired units require shorter flames to avoid flame impingement on the rear wall. The test results have shown that the short flame distributed mixing burner can be optimized for low NO emissions, but that deeper staging (low burner zone stoichiometry) is required. A distributed mixing burner could be designed to vary flame shape by incorporating some mechanism for changing the spreading characteristics of the primary and secondary airstreams. For burners designed with tangential inlets, this parameter is most easily varied by burner setback annular tangential inlets, this time in the primary/secondary mixing zone upstream of the burner throat. For burners designed with a central coal nozzle, impeller blades can be used to increase the coal spreading rate. In the short flame distributed mixing burners, optimum results were obtained with 45° impeller blades. However, the tests were of limited duration and did not evaluate erosion which may limit impeller life in burners operated for extended periods as in field boilers. A significant amount of data are not available to evaluate the effects of primary velocity. Consequently, distributed mixing burners should be designed to allow primary velocity to be varied during burner tuning. This could be achieved by designing for a low primary velocity and providing sleeves or other devices to reduce the nozzle exit diameter.

The air system design has a significant influence on NO and CO emissions. Dual secondary air channels provide additional control over fuel/air mixing rates and are thus preferred over the single secondary burner design. Burner zone stoichiometry is the major parameter controlling NO for the DMB and the lower limit will be dictated by CO or flame stability. Flame stability can be enhanced at lower burner zone stoichiometrics, however, by increasing the secondary swirl without impact on NO. Since the optimum value of swirl and burner zone stoichiometry will be dependent upon the burner characteristics, swirl device, and coal composition, as well as the overall duty cycle, DMBs should be designed with sufficient flexibility to vary this parameter. Although not explicitly discussed, the flame stability characteristics are also influenced by the primary air velocity. Capability to vary the primary air velocity will also provide an added means for operating at low burner zone stoichiometry while maintaining low CO levels. Tertiary jet velocity does not appear to be an important design parameter for NO or CO, although port location has a significant impact on CO burnout. For DMBs designed for field boilers, the location of tertiary ports will be determined in part by the burner-to-burner spacing and other furnace and windbox design parameters.

The burner exit configuration plays a key role in flame stability. For most of the distributed mixing burner tests, the primary and inner secondary setbacks were zero, the quarl divergence half angle was 25 degrees and its length was equal to the throat diameter. If this exit configuration is applied to DMBs for field boilers, the resulting quarl length and overall diameter will be considerably larger than current commercial practice. Consequently, a shorter quarl length will probably be required. The test results discussed above showed that flame stability decreased with quarl length, and it may be necessary to increase the coal nozzle setback or swirl on the primary or secondary airstreams to achieve satisfactory flame stability in a burner with a short quarl.

These general burner design requirements are summarized in Table 4-5. Several of the parameters are listed as site-dependent (S.D.) and must be based on the characteristics of the field boilers. It is possible that the nominal design point values may need to be varied for optimum burner performance. Thus, DMBs must be designed to be "flexible" so that the design parameters can be adjusted as required for optimum performance. Table 4-5 also lists the range of variables which should be examined as part of burner performance optimization tests.

Table 4-5. Prototype Burner Designs Parameters

Parameter	Nominal Design Point	Testing Range
Fuel System		
Primary Temperature (°F)	S.D.	130-180
Primary Stoichiometry (% T.A.)	S.D.	17-30
Primary Velocity (ft/sec)	75	50-90
Primary Swirl	45° Vanes	Variable
Air Systems		
Secondary		
Temperature (°F)	S.D.	400-650
Burner Zone Stoichiometry (% T.A.)	50-70	40-120
Inner Swirl	Variable	Variable
Outer Swirl	Variable	Variable
Axial Velocity (ft/sec)	60	50-90
Inner/Total Area	0.33	Variable
Inner/Total Flow Rate	0.33	Variable
Tertiary		
Temperature (°F)	S.D.	400-650
Swirl	None	--
Axial Velocity (ft/sec)	50	40-60
Angle (degrees)	0	--
Number	4	--
Location (radius/throat diameter)	2.2	S.D.
Divergence (degrees)	0	--
Exit		
Half Angle (degrees)	25	Variable
Length/Diameter	1.0	S.D.
Setback - Inner Secondary (inches)	0	Variable
Setback - Outer Secondary (inches)	0	Variable
Operational Variables		
Capacity (10^6 Btu/hr)	S.D.	--
Turndown (% capacity)	S.D.	≈50
Overall Stoichiometry (% T.A.)	S.D.	100-150

4.3 Comparison of General DMB Design Requirements with Standard Commercial Practice

Table 4-6 compares the general DMB design requirements (Table 4-5) with standard commercial burner practice. For most of the items listed the general DMB design requirements will require minor modifications to commercial practice. Exceptions are discussed below.

The most important difference between the distributed mixing burner and commercial practice is the tertiary air ports. These ports will require additional penetrations through the tube-wall and must incorporate an airflow control system. In the distributed mixing burners tested previously at EER, the airflows to each burner passage were measured with venturis and controlled by gate or butterfly valves. However, in commercial practice all of the combustion air (except for the primary) flows through a windbox. Airflow to the various DMB passages such as dampers or other control devices within the windbox controlled by a different method.

The air velocities through the primary and secondary channels are lower in the distributed mixing burner than in commercial practice. This will require larger fuel nozzles for the DMB. The secondary air passage and burner throat may not need to be enlarged because although the velocities are lower, a significant portion of the combustion air is diverted through the tertiary air ports.

The burner exits for the distributed mixing burners tested to date have been considerably larger than those of standard commercial burners. In field boilers, the burner exit length and outside diameter are limited by the furnace and windbox designs. Distributed mixing burners for field boilers must also conform to these constraints.

Table 4-6. Comparison of Prototype Burner Design Criteria with Standard Commercial Practice

System/Component	Standard Commercial Practice	Prototype Burner Design Criteria
● Fuel Injector		
- % of total air	10-40	20
- Injection velocity at max load	75-90 fps	75 fps
- Minimum injection velocity	50 fps	50 fps
- Mechanical spreader	Used by some manufacturers	Depends on desired flame shape
● Fuel System		
- Flow control and measurement	Feeder speed	Feeder speed
- Multifuel capability	Gas, oil, wood, COM	Same as host site
- Turndown range	3-4	3
● Combustion Air Systems		
- Primary velocity	50-90 fps	75 fps at max rating
- Secondary velocity	~100 fps at max rating	60 fps at max rating
- Secondary swirl	High	Low-medium
- Excess Air	15-30%	~15%
- No. of secondary channels	One or two	Two
- No. of tertiary ports	Not applicable	Four
- Secondary air flow control and measurement	Registers for control, no individual burner measurement	Integrated control & measurement (see text)
- Windbox	Compartmented on a few new units otherwise open	Open
- Overfire air	Rare for industrial boilers	None
● Burner Exit		
- Half angle	20-60°	25°
- Construction	Tubes, ceramic w or w/o studded tubes	Tubes, ceramic w or w/o studded tubes
● Lighter		
- Fuel	Oil, gas, electric	Same as host site
- Duty	Continuous, on during load changes	Continuous
● Control System		
- Ignition sequence	Manual or automatic	Manual
- Response to steam demand	Automatic	Automatic
● Safety System		
- Main fuel shutoff	Automatic or manual based on lighter and/or main flame	Automatic based on lighter or main flame
- Type of flame detection	UV or flicker	Same as host site

5.0 COMMERCIAL BURNER TESTING

Since a primary goal of the program is to demonstrate the DMB technology in field operating boilers, some assurance is required that the DMB, which has only been demonstrated in the LWS research furnace, will also perform in the field as predicted. Also, the basis for the prototype design is the research furnace (LWS) and not a steam raising system. Although indirect, the approach taken was to evaluate commercial burner operation in the LWS and compare it against field experience. This approach provides some assurance that if the burner operates satisfactorily in the LWS, it will also operate satisfactorily in the field.

The burners selected for testing under this program are:

- Babcock and Wilcox Dual-Register burner
- Peabody Engineering Corporation standard pulverized-coal burner with low NO_x modification
- Steinmuller low-NO_x burner. The burner is similar to the burners currently used at the Weir plant in West Germany

All the burners are designed for a nominal firing rate of 50 x 10^6 Btu/hr, and the installation in the LWS is similar to that in the field. To date, the B&W and Peabody burners have been tested with the baseline Utah bituminous coal. The Steinmuller burner is on-site and preparations are being made for testing in 1980. This burner will be tested with a bituminous coal from Germany, which is similar to the coal used in the field, along with the baseline Utah coal. The results from the B&W and Peabody burners will be described below. In support of the Industrial Demonstration Program (68-02-3127) an 80 x 106 Btu/hr, Foster Wheeler Intervane Burner (pre-NSPS) was also evaluated and is included in this report for completeness.

5.1 Description of Commercial Burner Designs

5.1.1 Babcock and Wilcox Dual-Register Burner

The installation of the B&W Dual-Register burner in the LWS was consistent with standard installation in the field with two exceptions: 1) the quarl was made of refractory and was deeper than normally found in the field and 2) the windbox had a partition between the inner and outer secondary air channels. The quarl size and shape were identical to that used at the Babcock and Wilcox Research Center, Alliance, Ohio. A schematic of the 50 x 10^6 Btu/hr burner is shown in Figure 5-1. Hardware and operating specifications obtained from the manufacturers are included in Table 5-1. The burner consists of three concentric flow channels: (1) a central primary passage (coal plus transport air); (2) an inner secondary, and (3) an outer secondary air channel. In commercial application, combustion air to the different secondary channels is supplied from a common windbox. The coal is fed directly to the burner from a C-E Raymond mill.

Pulverized coal is tranpsorted into the primary air pipe via a venturi-type coal distributor. The primary air pipe is 10.5 inches in diameter and terminates at three inches recessed from the burner quarl. With 20 percent of the theoretical air requirement at 50 x 10^6 Btu/hr as primary air, the injection velocity is about 50 ft/sec at 200°F.

Inner secondary air flows into the inner annular channel (19.75 inches OD) around the primary pipe via a cylindrical air register with eight movable doors. The movable doors are primarily designed to control the amount of airflow, but are arranged such that the air flows in a clockwise direction when looking along the direction of flow. Inside the annular channel eight movable swirl vanes are present to produce tangential momentum in the secondary air in either the clockwise or counterclockwise direction. Babcock and Wilcox recommends that about 30 percent of the air be introduced into the inner secondary passage. At 600°F the air velocity is about 83 ft/sec. The inner secondary air channel terminates at the same position as the primary air channel (i.e., three inches recessed from the quarl section). Outer secondary air flows through the next annular channel around the inner secondary air. A cylindrical air register with 12 movable doors (arranged in clockwise direction) is used to control the amount of air, as well as introduce some tangential momentum. This air channel terminates at the quarl and produces an air velocity of about 135 ft/sec at air temperatures of 600°F.

The burner quarl is 5-7/16 inches long with a throat diameter of 20-1/4 inches and a half-angle of 20°. While for commercial boilers, water tubes are bent to form the quarl, in the LWS facility a refractory quarl is used.

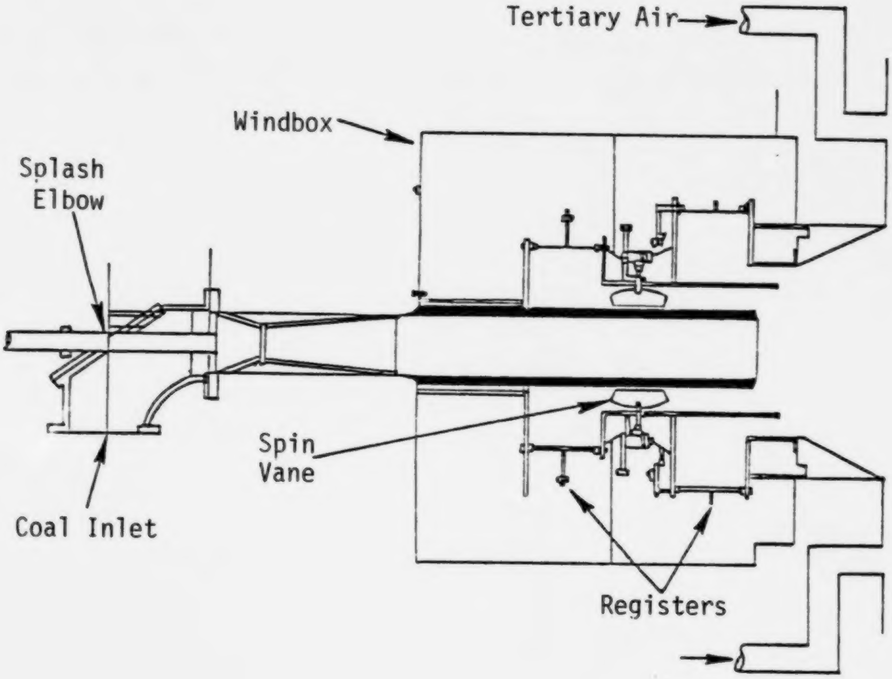

Tertiary Air
Windbox
Splash Elbow
Spin Vane
Coal Inlet
Registers

Figure 5-1. Installation of B&W Dual-Register Burner in LWS.

Table 5-1. Babcock and Wilcox Burner Design Point Operation Specifications

Stream	Operating Temp. ^oF	Mass Rate lb/min	Vol. Rate @ ^oF ft^3/min	Vol. Rate @ Operation Temp.	Velocity ft/sec
Coal	200	68	NA	NA	NA
Primary	200	136	1820	2270	50.0
Inner Secondary	600	232	3115	6230	83.5
Outer	600	406	5447	10,890	138.3

Load: 50×10^6 Btu/hr

5.1.2 Peabody Dual Register Burner

The burner supplied by Peabody Engineering Corporation is typical of burners found in present Peabody coal fired heater installations. A sketch of the burner is shown in Figure 5-2. It consists of three concentric channels: the inner or secondary stream which contains air only; the first annulus or primary stream which contains transport air plus coal; and the outer channel or tertiary air. In addition, outboard air channels were installed in the furnace for deep staging experiments to explore the low NO_x potential with this configuration. A schematic of the burner as seen from the furnace is presented in Figure 5-3. Detailed dimensions for all configurations evaluated are presented in Table 5-2.

The burner is unique in that a number of mixing schemes can be generated by the hardware accessories available. Some of these configurations are in sharp contrast to those under current development. For comparative purposes, the three configurations tested in this series are also shown in Figure 5-2, along with the basic standard installation. The configurations can be characterized as follows:

Basic Commercial Burner Configuration (I)

1. Early mixing of coal and air occurring prior to ignition. The effective stoichiometry of the coal mixture entering the throat is relatively lean.

Configuration (II)

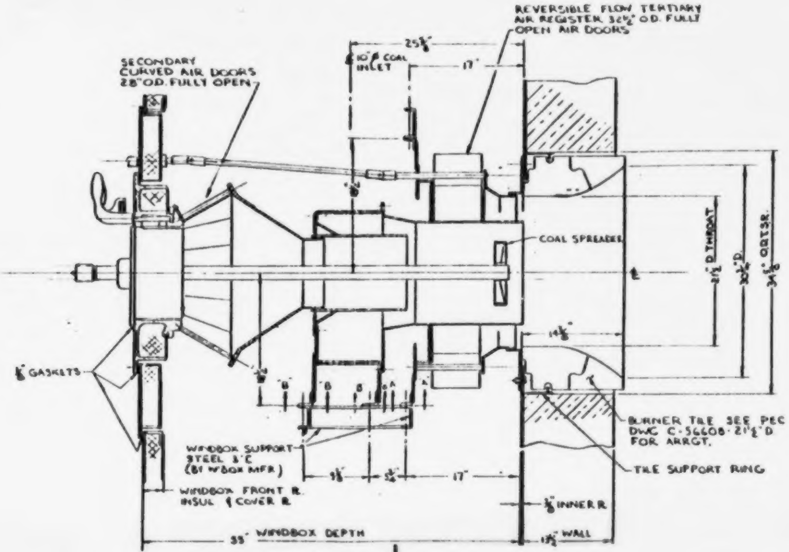
2. Mixing of inner two streams delayed until entrance to throat.

Configuration (III)

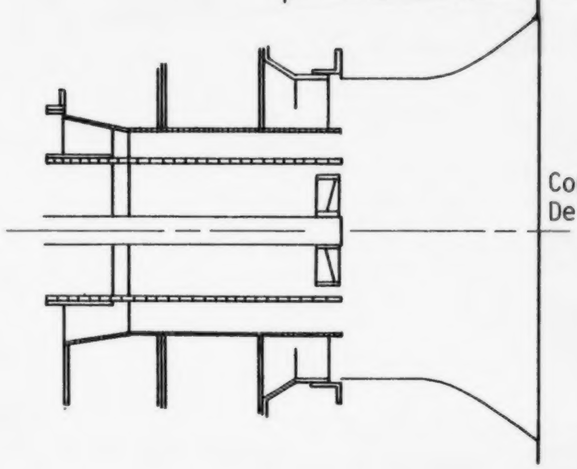
3. Mixing of inner two streams delayed until throat, but increased turbulent mixing in throat caused by impinging the coal stream upon the secondary air stream.

Configuration (IV)

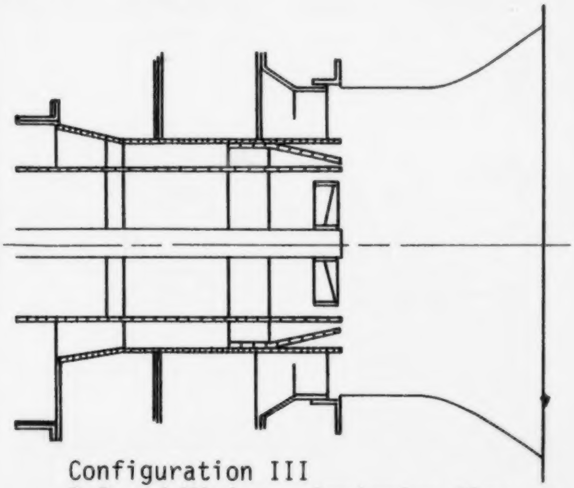
4. Early mixing of coal and air and injection at high velocity into the burner throat.


REVERSIBLE FLOW TERTIARY AIR REGISTER 32½" O.D. FULLY OPEN AIR DOORS
SECONDARY CURVED AIR DOORS 28" O.D. FULLY OPEN
25⅜"
10" ∅ COAL INLET
17"
COAL SPREADER
21½" D THROAT
30½" D
34⅛" QRTSR.
14⅜"
⅛" GASKETS
B
B
B
A
A
BURNER TILE SEE PEC DWG C-56608-21½" D FOR ARRGT.
TILE SUPPORT RING
WINDBOX SUPPORT STEEL 3" C (BY W'BOX MFR)
WINDBOX FRONT R. INSUL & COVER R.
17"
⅜" INNER R
35" WINDBOX DEPTH
13½" WALL

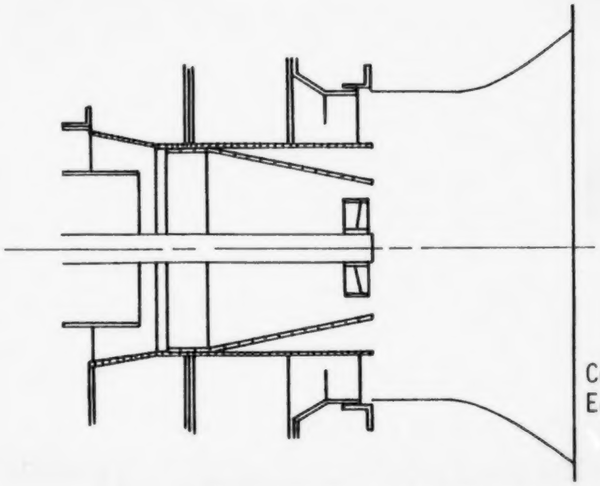
Baseline Burner Configuration
(Early Mixing)



Configuration II
Delayed Mixing



Configuration III
Delayed Mixing - Impinging Flow



Configuration IV
Early Mixing - High Velocity

Figure 5-2. Peabody Burner and Various Configurations Tested.

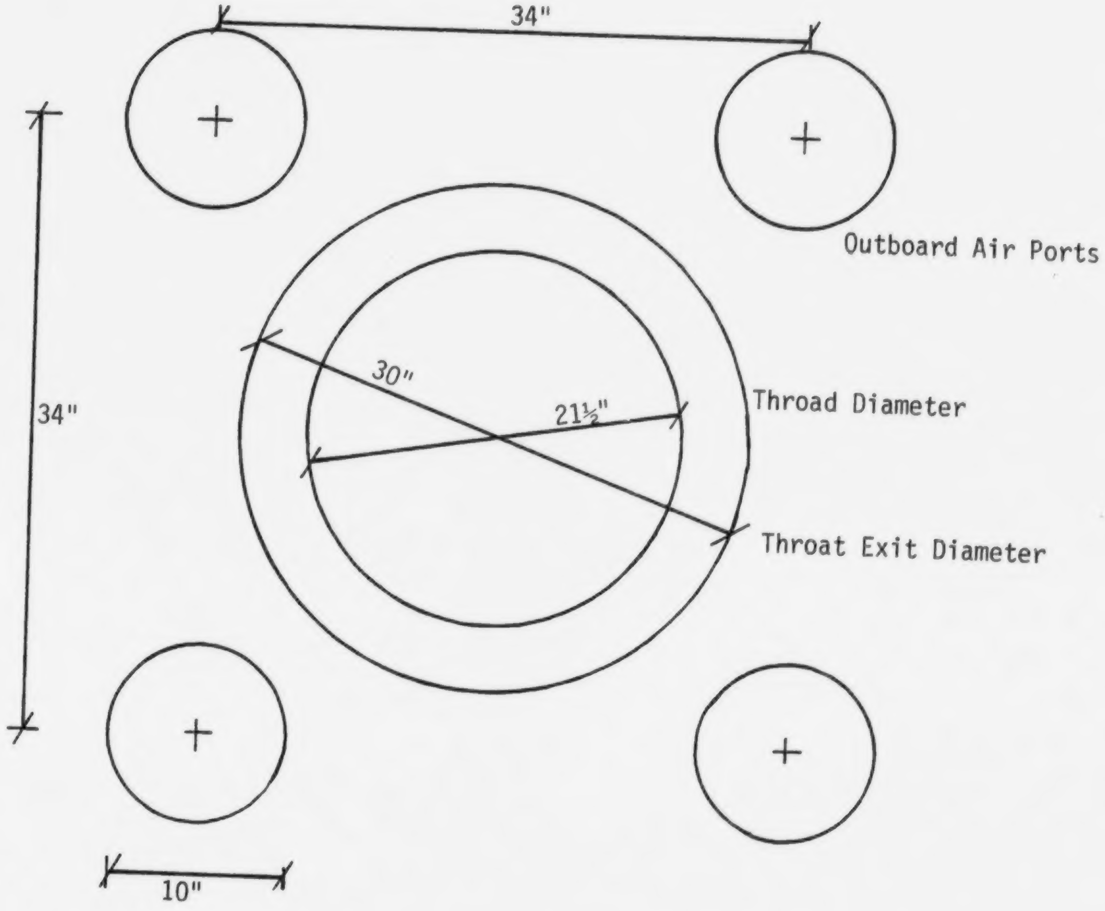

34"
Outboard Air Ports
34"
30"
21½"
Throad Diameter
Throat Exit Diameter
10"

Figure 5-3. Schematic of Peabody Showing the Location and Distribution of Outboard Air.

Table 5-2. Design Parameters for Peabody Burner (Baseline Configuration)

Dimensions		Operating Conditions		Velocities*	
Primary Diameter (in.)	14-1/2	Firing Capacity (10^6 Btu/hr)	50	Primary (ft/s)	60
Primary Area ($in.^2$)	72.3	Primary Stoich. (% T.A.)	18	Secondary (ft/s)	186
Secondary Diameter (in.)	10-3/8	Secondary Stoich. (% T.A.)	60	Tertiary (ft/s)	115
Secondary Area ($in.^2$)	79.6	Overall Stoich. (% T.A.)	120		
Tertiary Diameter (in.)	21-1/2	Primary Temp. (^oF)	150		
Tertiary Area ($in.^2$)	185.8	Secondary Temp. (^oF)	450		
Coal Spreaders Diameters (in.)	7, 8, 9	Tertiary Temp. (^oF)	450		
Outboard Diameter (in.)	10				
Total Outboard Area ($in.^2$)	314				

*Velocities based on Utah 2 Coal: T.A. = 1.029×10^{-2} scf/Btu.

The coal stream is delivered to the burner nozzle with tangential momentum due to the entry pattern and each configuration has a spreader located at the entrance of the throat. The purpose of the spreader device is to enhance ignition and provide flame stability by promoting recirculation of hot combustion gases near the burner exit.

Engineers from Peabody Engineering were on-site during most of the testing. They assisted in the start up and tuning of the burner and, according to their judgment, the installation, as well as burner operation, were similar to that observed in the field.

5.1.3 Foster Wheeler Intervane Burner

The Intervane burner is Foster Wheeler's standard commercial pulverized coal burner and is designed to produce rapid fuel and air mixing as well as a stable flame over a wide range in operating conditions. The resulting flames are short and intense, and compatible with both small and large furnace depths. This burner was fabricated and tested as part of a companion EPA Program 68-02-3127.

The burner has a nominal firing capacity of 90 x 10^6 Btu/hr and is shown schematically in Figure 5-4. The coal is delivered to the coal nozzle through a tangential inlet which imparts swirl to the primary coal/airstream. The coal is thrown radially outward by centrifugal force to the outer wall which has a series of "intervanes" to distribute the coal uniformly about the circumference. The coal nozzle is tapered inward from the inlet to the exit, which is generally located at the burner throat. Secondary combustion air is supplied to the windbox and enters the burner throat through a single adjustable register. The register is normally adjusted when the burner is first installed and periodically, as required, by routine maintenance. It is not usually adjusted during load or excess air changes. The center core of the burner is also supplied with air from the windbox. This air provides cooling for the coal nozzle and represents only a small fraction of the total combustion air. The burner exit has a long cylindrical portion and a short divergent portion on the exit end. In field installation the exit is formed from water-wall tubes and coated with refractory to match the desired contours.

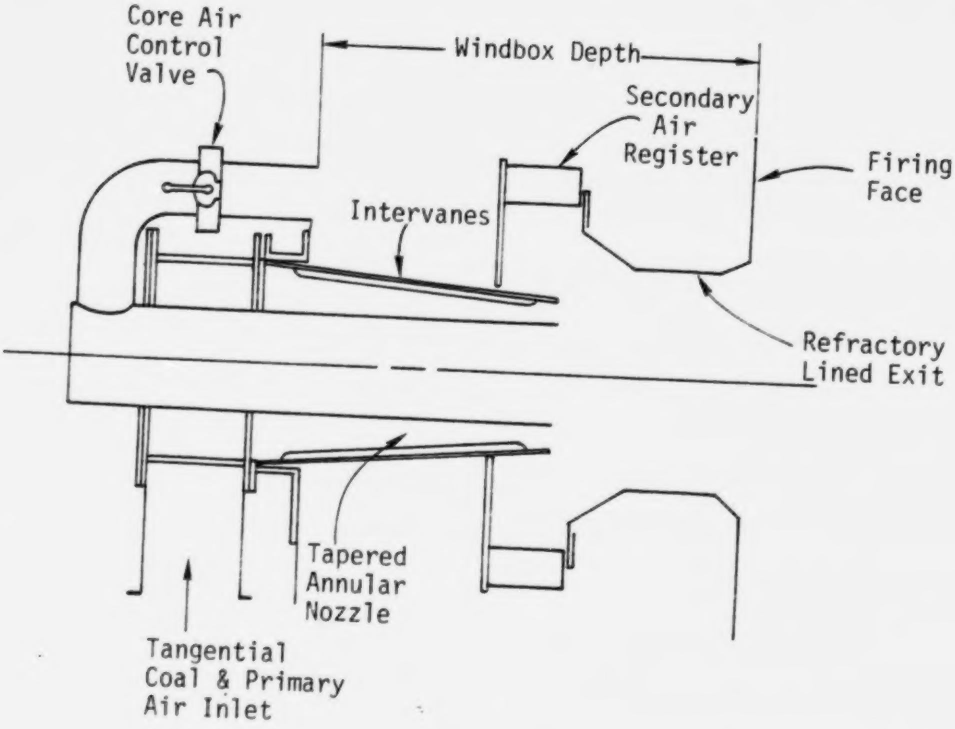

Core Air Control Valve
Windbox Depth
Secondary Air Register
Firing Face
Intervanes
Refractory Lined Exit
Tapered Annular Nozzle
Tangential Coal & Primary Air Inlet

Figure 5-4. Foster Wheeler Intervane Burner.

Table 5-3 lists the Intervane burner dimensions, full load operating conditions and velocities. Since the secondary air enters the throat nonaxially, the secondary area and velocity are not clearly defined. The values listed are based on axial flow in the equivalent annulus between the nozzle exit and throat and on the characteristics of the Utah coal used in the previous burner tests.

5.2 Commercial Burner Experimental Results

5.2.1 Babcock and Wilcox Dual Register Burner

The testing plan for the burner included the following main items.

- Initial testing and burner tuning
- Standard practice characterization
- Low NO_x potential evaluation

The general features of the flame from the Dual Register Burner were that the flame was typical of the slow diffusion mixing and resulted in a long narrow flame. The flame was, in fact, longer than the LWS furnace depth (16 ft) and resulted in excessive impingement of the flame on the back wall. As a consequence of this, incomplete combustion of the coal occurred, resulting in rapid accumulation of residue in the bottom of the furnace and a very black exit plume. Apparently this type of operation is, however, not atypical to that which occurs in the Alliance Research Center Stirling boiler (12 ft firing depth) which is used as a basis for commercial burner design. In fact, it was noted that the general flame characteristics in the LWS were about the same as those observed in the Stirling boiler, but that in multiburner field operating boilers the flames from dual register burners are somewhat more narrow. However, direct comparison of test results from impinging flame burners with those from comparipinging flame burners is not possible because flame impingement significantly alters burner performance: the overall flame shape is altered, CO and unburned carbon losses are increased and NO is decreased. Consequently, the conclusions drawn from tests with the Dual Register Burner must be qualified because the effects of impingement cannot be quantified.

Table 5-3. Intervane Burner Characteristics.

Dimensions	
Core Diameter	12.0
Core Area (in.^{2})	113.0
Nozzle Diameter (in.)	18.5
Primary Radial Thickness (in.)	2875
Primary Area (in.^{2})	141.1
Throat Diameter (in.)	28.0
Secondary Radial Thickness (in.)	4.75
Secondary Area (in.^{2})	346.9
Throat Area (in.^{2})	615.7
Nozzle Setback from Firing Face (in.)	24.0
Operating Conditions	
Firing Capacity (10^6Btu/hr)	90.0
Air Requirement (lb air/10^6 Btu)	7.57*
Primary Stoichiometry (% T.A.)	18
Primary Temperature (^{o}F)	150
Overall Stoichiometry (% T.A.)	120
Windbox Temperature (^{o}F)	600
Velocities	
Primary (ft/sec)	52.2
Secondary (ft/sec)	213.7
Throat (ft/sec)	132.6

*Based on Utah Coal

The NO and CO characteristics for the Dual Register Burner tested in the LWS are shown in Figure 5-5. The full load excess air characteristics (Figure 5-5A) show that CO increased as the excess air was decreased below 140 percent T.A. At a typical boiler excess air of 125 percent T.A. the CO level was 500 ppm. CO also decreased as load was reduced even though the excess air was maintained high (6 percent O_2 or 138 percent T.A.). These characteristics are substantially different from the burner performance which has been observed in field tests. The table below compares the LWS test results with field data from a 550 MW opposed bituminous coal-fired boiler equipped with B&W Dual Register burners.

Load (% of full)	Excess O_2 (%)	NO (ppm)*		CO (ppm)*	
		LWS	Field	LWS	Field
100	4.0	125	470	500	40
80	6.0	175	470	675	28

* @ 0% O_2, dry

Experiments to utilize the outboard tertiary air ports to reduce the NO_x emission by deep staging in a manner similar to the DMB were not completely successful, due to the combustion characteristics of this burner. However, a limited test series was conducted to evaluate the impact of burner zone stoichiometry on NO & CO characteristics. The results are shown in Figure 5-6. These results show that reducing the stoichiometry in the burner zone provides reductions in NO similar to that obtained with the DMB under staged conditions.

Under unstaged conditions, grab samples of fly ash residue were taken from the exhaust gas and analyzed for nitrogen content (these samples may not be representative of the total emissions). Based upon ash as an inert tracer these data indicate that approximately 10-15% of nitrogen input to the furnace leaves as unburned residue. It is believed that this estimate is conservative. The less dense particulate that would be collected as fly ash would be expected to exhibit higher burnout than those found in the bottom ash. The accumulation of bottom ash was markedly more than with other burners tested in the LWS to date. (It was not possible to obtain a representative sample of bottom ash that was not contaminated with coal.)

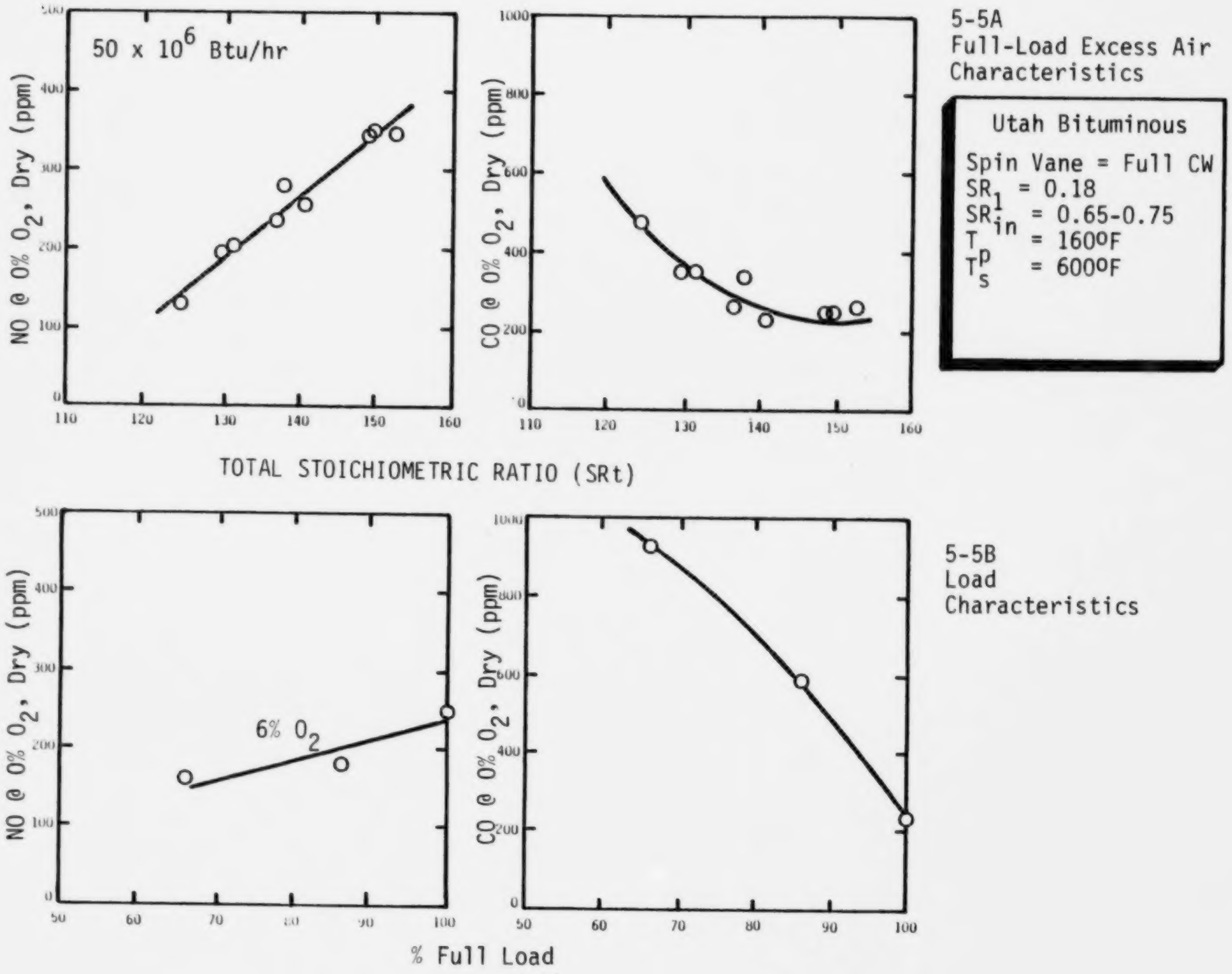


Figure 5-5. Performance/emissions Characteristics for Babcock/Wilcox DRB in LWS - Single Burner.

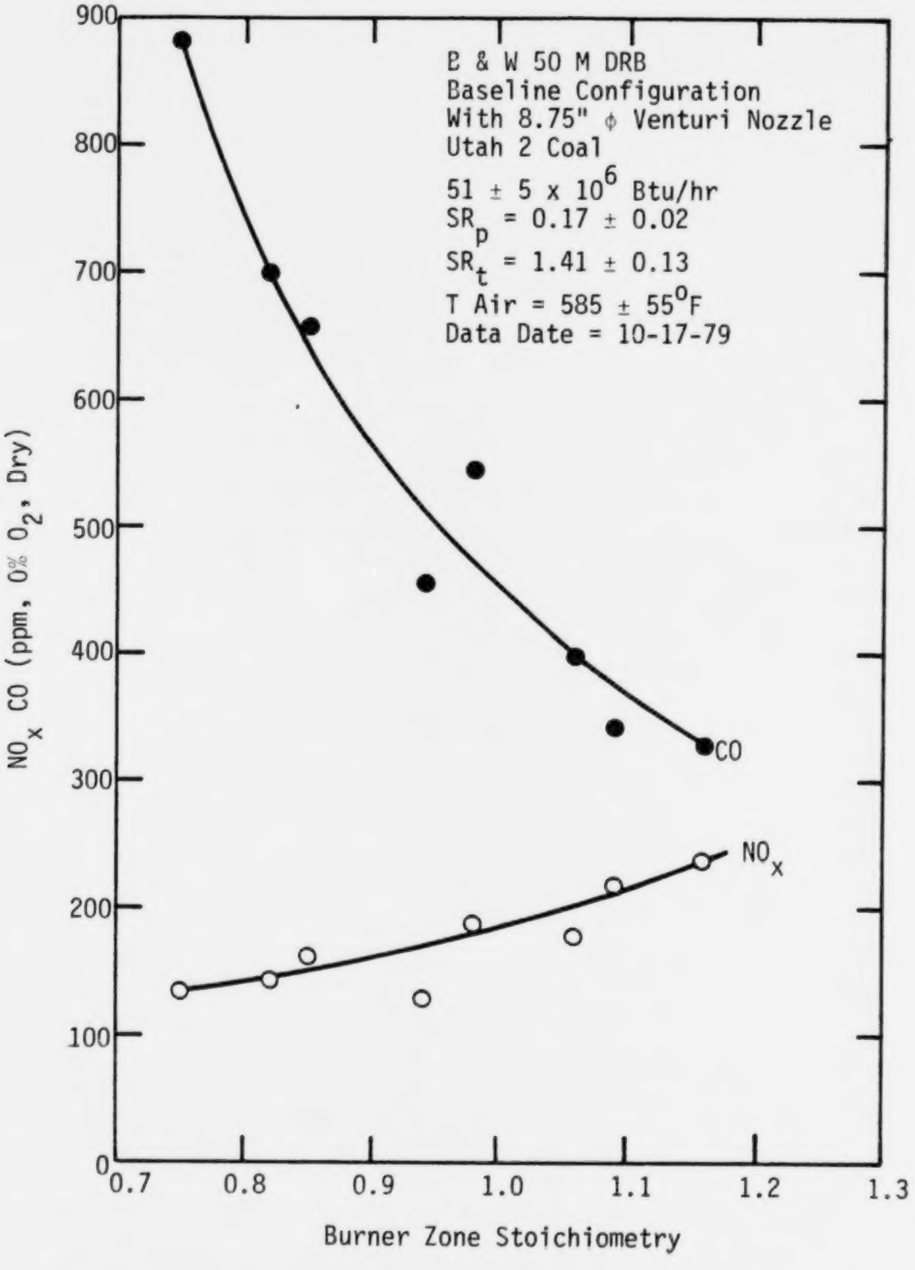


Figure 5-6. NO and CO Emissions at Different Burner Zone Stoichiometries.

In Summary, the baseline tests with the B&W Dual-Register burner in the LWS were characterized by poor burnout of the coal. This was caused by the slow mixing characteristics of the long flame impinging on the back wall of the LWS. Because of the poor burnout, the emissions data must be treated with caution. The comparison of the data collected with field data generally showed that NO levels were lower and CO concentrations were higher.

5.2.2 Peabody Dual Register Burner

5.2.2.1 Basic Commercial Configuration (#1)

This configuration is representative of field installed burners and is therefore considered as the baseline burner. For this configuration, the flame shape was generally divergent and about 8-12 feet long. Ignition appeared to be occurring near the mid-point of the throat and the flame color was indicative of intense combustion. The baseline NO characteristics presented in Figure 5-7 reveal that they are very similar to that of other burners. Carbon monoxide, however, increases over the entire stoichiometry range evaluated and the levels are higher than anticipated. Visual observation of the flame showed that the mixing appeared to be uniform and intense, and the exhaust plume opacity was low.

5.2.2.2 Modified Burner Configuration

The three other configurations discussed in the previous section were also evaluated in limited testing. These configurations were selected to provide a broad range in burner mixing characteristics, together with staging of the burner using the air ports in a manner similar to the DMB. For example, in Configuration II the changes consisted of extending the secondary duct out to the entrance of the throat in addition to employing a smaller diameter spreader. In this way, the inner, secondary air and the coal experience no premixing prior to the burner throat. The physical characteristics of the flame were similar to the baseline burner, but the combustion appears to be more intense as judged by a brighter flame. It also appeared that ignition was occurring deeper into the throat than the baseline burner. This is different than that anticipated since it was intuitively felt that delaying the initiation of mixing would result in a longer, slower mixing flame and ignition

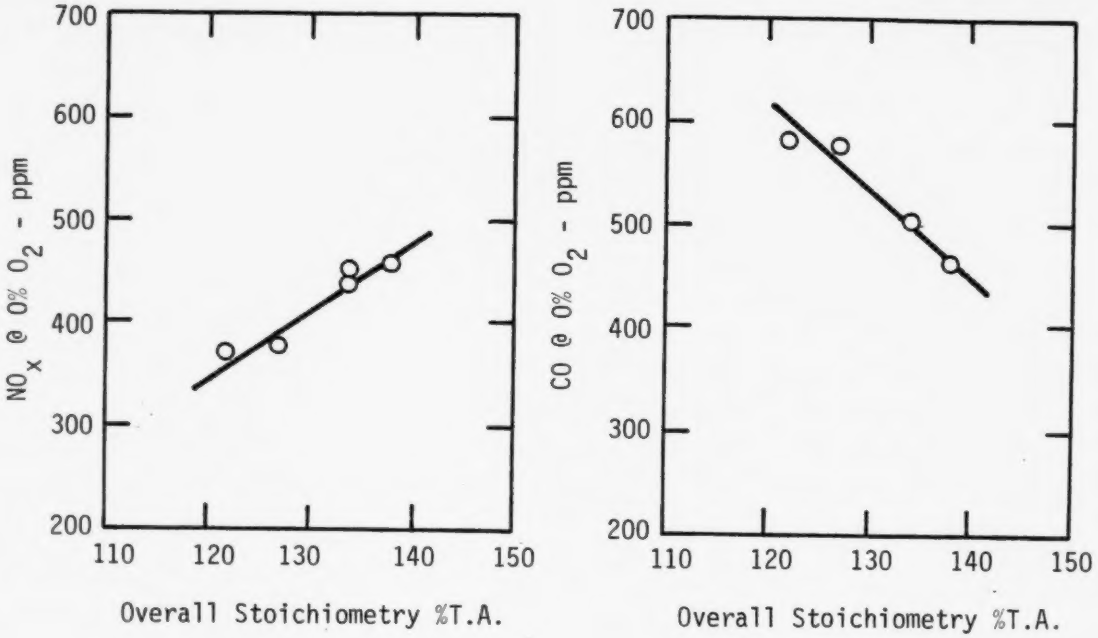


Figure 5-7. Basic Peabody Commercial Burner (Configuration #1) Performance/Emissions Characteristics.

further downstream of the burner exit. Comparing the NO levels with the baseline burner in Figure 5-8, it is also shown that this configuration resulted in higher overall NO, which is consistent with the more intense flame characteristics.

Configuration III consisted of using a device to deflect the coal/air stream into the swirling secondary core stream, as was shown in Figure 5-2. Ignition occurred well into the throat and the combustion was very intense. The flame shape and length were similar to Configuration II. Due to the limited nature of the data, the staging results are shown as a dashed line in Figure 5-8 (as was done with the baseline burner). Note that the NO levels were extremely high approaching 800 ppm at 135 percent theoretical air. These NO levels represent the highest yet achieved in the LWS.

The final configuration was similar to that of the baseline burner, but with a converging nozzle inserted into the primary stream, as shown in Figure 5-2. Due to facility malfunctions, sufficient data were not obtained to provide a plot of the results. However, some general characteristics of the burner can be described. The flame was very intense and ignition was occurring almost at or slightly before the exit plane of the coal stream. The NO levels appears to be considerably higher than the baseline configuration.

The results from this burner dramatically demonstrate the sensitivity of NO to the burner mixing characteristics. Further analysis of these results must await the time when the burner can be tested on the cold flow facility in order to better define the burner flow characteristics at the throat. This should be accomplished during the next reporting period.

5.2.3 Foster Wheeler Intervane Burner (Pre-NSPS)

The Intervane burner operational characteristics were also evaluated in the LWS over a range in excess air and load. The burner installation and firing system were first checked by a qualified Foster Wheeler Service Representative to ensure that they conformed to practice. The Representative Field Engineer then supervised the burner start-up and adjustment of controls

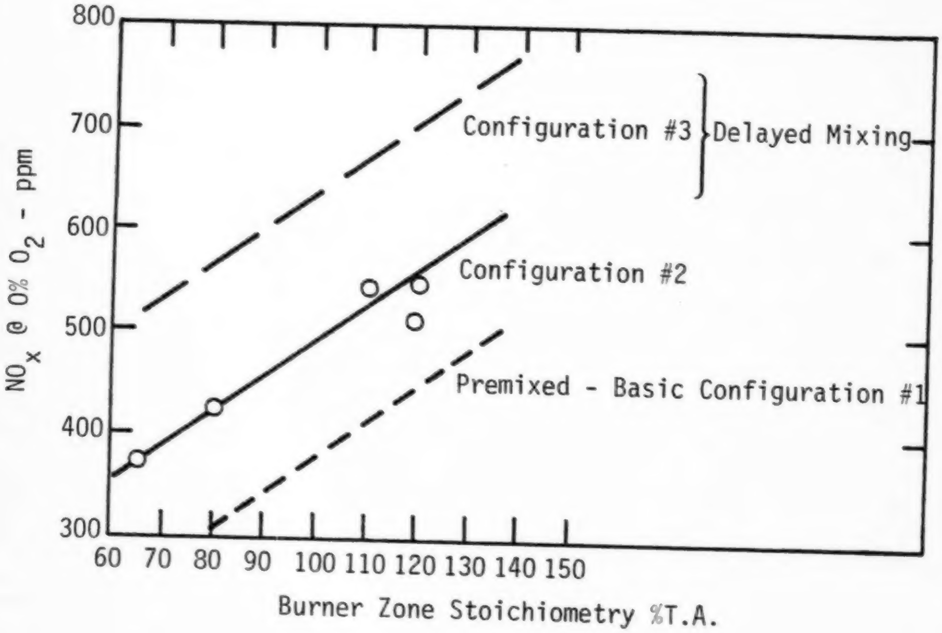
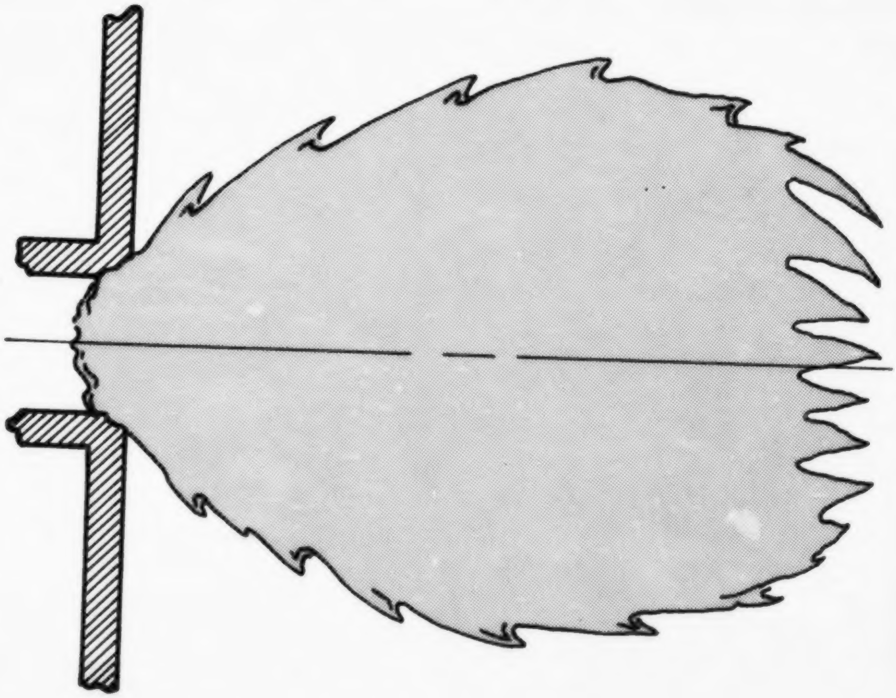


Figure 5-8. Comparison of Several Configurations of the Peabody Dual Register Burner.

to establish the full load operating point providing acceptable flame shape/length and performance characteristics. At this burner setting the input coal and airflows were then varied (identical to that in field operation) over the operating load range and at near full load over a range in excess air.

In general, the flames produced by this burner were short, bright, intense and stable. As shown in the sketch below, the base of the flame was within the cylindrical portion of the exit and filled the divergent section. In the furnace, the flame expanded rapidly and was about 12 feet (five throat diameters) long. The burner controls (register and core air control valve) affected the flame shape and optimum results were obtained with the register set at 40° open and the core air valve set at 78° open. These settings are similar to those used in field installations, but the flame shape in the LWS was somewhat narrower and longer than those observed with multiburner arrays in the field. Throughout the tests stack opacity was low except for low excess air conditions where some black smoke was observed. The smoke was generally a light gray haze.



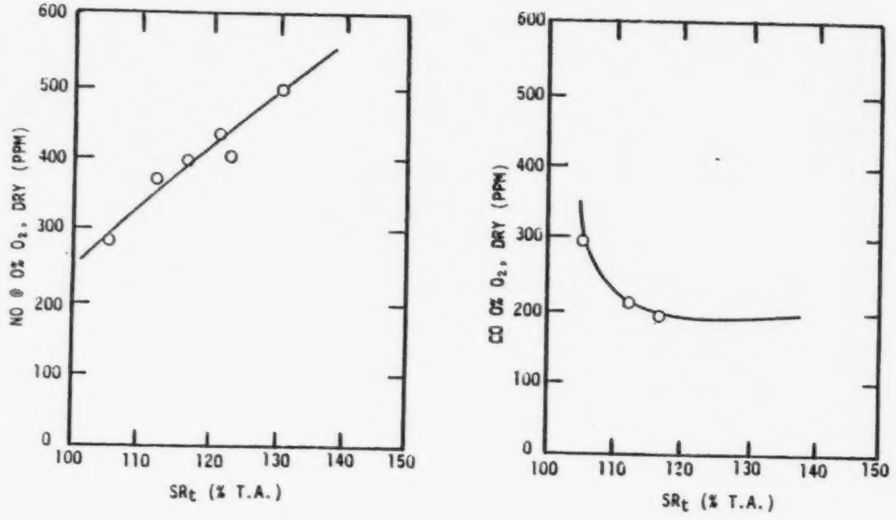
The NO and CO characteristics for this burner are shown in Figure 5-9. The excess air results shown in Figure 5-9A are for a load of 80 x 10^6 Btu/hr heat input and reveal that the NO level at 125 percent excess air is 450 ppm. (It should be noted that the MCR for this burner is about 90 x 10^6 Btu/hr which results in an NO level of 500 ppm.) These levels are 50 to 100 ppm lower than expected in a multiburner field unit of similar burner zone heat release rate; however, the variation in NO with excess air is within normal field observed ranges. The CO characteristics, also shown in Figure 5-9A were more sensitive to variations in excess air than observed in the field. For example, in field units it is expected that the sharp rise in CO would occur at lower values of excess air (110 percent TA) than that shown in Figure 5-9A. In addition, the asymptotic value of CO measured in the LWS was about 185 ppm (corrected to 0 percent O_2) which is greater by a factor of four than that observed in multiburner field units.

The burner NO/CO performance characteristics are shown in Figure 5-9B. The load was varied from about 45 x 10^6 Btu/hr heat input to about 80 x 10^6 Btu/hr. Based on an MCR of 90 x 10^6 Btu/hr this represents a variation in percent of full load from about 50 percent to 90 percent. Over this range the burner operated very stable; however, at the lower load steady-state coal feed rate was difficult to maintain. This problem was not related to the burner, but to the turndown capability of the C.E. mill at the required coal-to-air ratios representative of Foster Wheeler MB mills. Figure 5-9B also shows typical field data from an array of four Intervane burners of the same capacity (90 x 10^6 Btu/hr). The slope of the NO versus load characteristic for the field data is steeper than for the LWS test results. At the lowest load tested, 50 percent of full load, the field and LWS NO levels are almost identical. The CO levels measured in the LWS were nearly constant over the load range increasing about 50 ppm or 25 percent at the lowest load. The field CO data is also nearly constant, but substantially lower as discussed above.

5.3 Comparison of Operating Characteristics of Commercial Burners in LWS with Field Experience

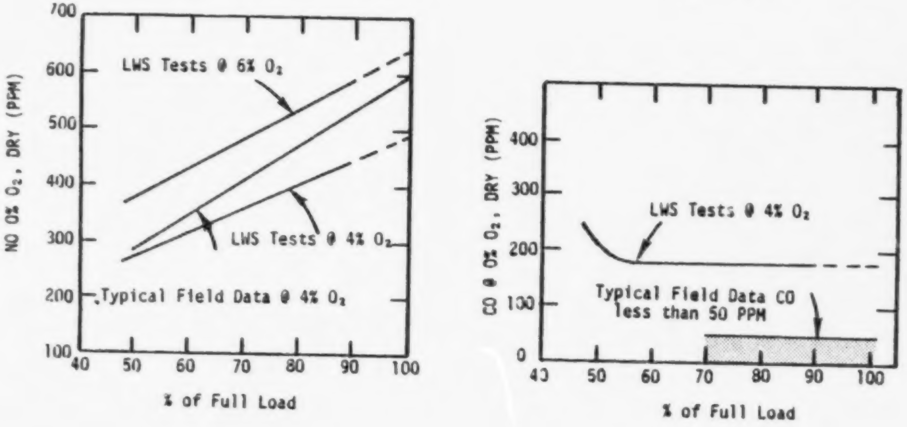
There are several general conclusions that can be made from these test results. They are:

5-9a
Excess Air
Characteristics
@ 80 x 10^6 Btu/hr



TEST CONDITIONS
Register = 40° Open
Core Value = 78° Open
SR_p = 18% T.A.
T_p = 160°F
T_s = 600°F

5-9b
Load
Characteristics
and Field Data



TEST CONDITIONS
Register = 40° Open
Core Value = 78° Open
T_p = 160°F
T_s = 600°F
SR_p = Follows Field Condition

Figure 5-9. Performance/emissions Characteristics for Foster Wheeler Intervane Burner.

1. The general flames observed in the LWS were judged, by experienced engineers, to be very similar to those in the field.
2. CO levels are consistently higher than obtained in the field. A lower limit of about 200 ppm was obtained for all burners.
3. The NO levels were lower in the LWS than the field for the B&W Dual-Register burner.
4. It is possible to reduce the NO in a well-mixed burner by about 50 percent with outboard staging techniques, and the minimum NO obtained appears to be independent of burner design.

Commercial burner manufacturers have found that the NO_x levels produced by their burners in boilers of their design can be approximately correlated with the total heat liberation per unit surface area in the furnace. One major limitation in applying these correlations to the LWS is that they are highly empirical in nature, and can only be applied to certain specific burner and furnace designs. However, the burner manufacturers have found that when two burners are tested in a research facility such as the LWS, the ratio of NO_x emissions as measured in the test facility under comparable conditions will be comparable to the ratio of NO_x emissions when operated in field boilers. The tests of the Foster Wheeler Intervane burner and the Babcock and Wilcox Dual-Register burner in the LWS and the field test data presented in the previous section help provide a basis for estimating DMB performance in the field.

The NO characteristics for the three commercial burners are presented in Figure 5-10. In comparing the NO characteristics for the Foster Wheeler and B&W commercial burners it is not surprising that the pre-NSPS Foster Wheeler Invervane burner (90×10^6 Btu/hr) resulted in the highest value of NO. However, since published field data suggests that the CO levels for the two burners should be similar, the much higher CO level for the Babcock and Wilcox burner (factor of 2.5) must be attributed to excessive wall impingement. Further, field experience also shows that the dual register burner should operate at about 330 ppm (at 3 % O_2) corrected for the burner heat release rate of the LWS. This represents a difference in NO of about 230 ppm which is considerably greater than the results from the Intervane burner. This suggests that the excessive wall impingement is also affecting the NO levels for the Babcock and Wilcox burner.

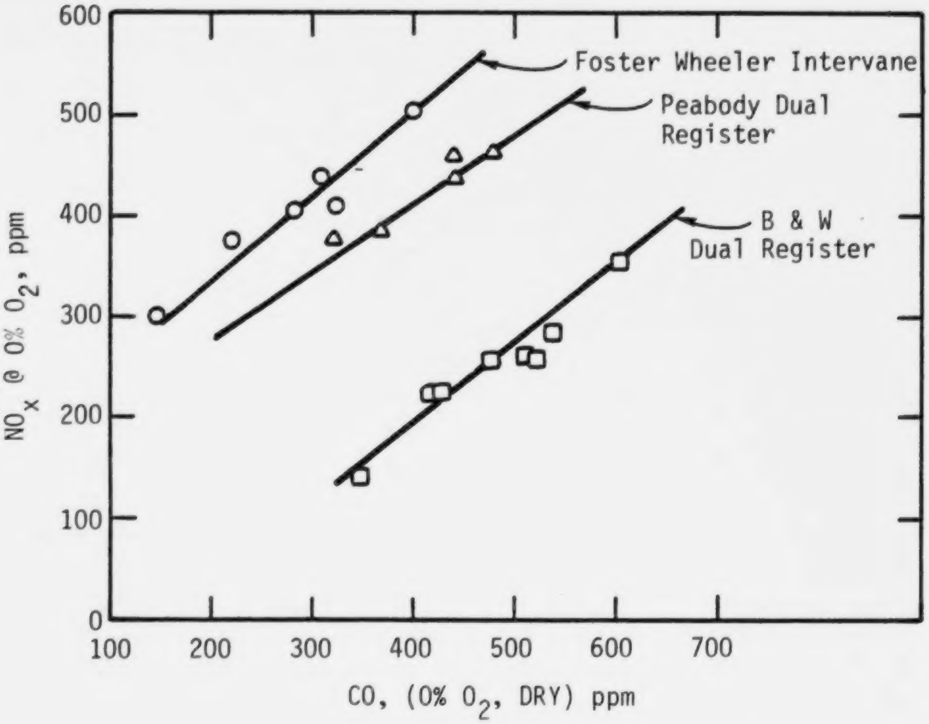


Figure 5-10. Comparison of Commercial Burner Operation in LWS.

APPENDIX A

Coals

		Page
A-1	Coals Available and Legend	A-2
A-2	Coal Source	A-4
A-3	Sulfur Forms	A-8

A-1

Summary of Numbers and Symbols
Associated with the Various Coals

Designation	Location	Coal	Symbol
WKC	W. Ky.	High Volatile A Bituminous	◇
TRW #1		High Volatile A Bituminous	⏢
TRW #2	W. Va.	High Volatile A Bituminous	⌂
TRW #3	W. Ky.	High Volatile B Bituminous	⛉
Utah-I	Price, Utah	High Volatile B Bituminous	○
Utah-II	Price, Utah	High Volatile B Bituminous	◺
#1	Coalstrip, Montana	Subbituminous B	▽
#2	Farmington, N.M.	High Volatile C Bituminous	◸
#3	Fruitland, N.M.	High Volatile C Bituminous	⬡
#4	Scranton, N.D.	Lignite A	◊
#5	Kemmerer, Wyoming	Subbituminous A	◗
#6	Beulah, N.D.	Lignite A	⬡
#7	EPA, Colorado	High Volatile A Bituminous	⬨
#8	Hardin, Montana	Subbituminous B	⬠
#9	Beulah, N.D.	Lignite A	□
#10	Velva, N.D.	Lignite A	D
#11	Savage, Montana	Lignite A	△
#12	Peonia, Colorado	High Volatile C Bituminous	∪
#13A	Cadiz, Ohio	High Volatile A Bituminous	⊲
#13B	Cadiz, Ohio	High Volatile B Bituminous	▢
#14	Buffalo Mark, W. Va.	High Volatile A Bituminous	⬡
#15	Elkay, W. Va.	High Volatile A Bituminous	⬠
#16	Sewanee, Alabama	Medium Volatile Bituminous	⬯
#17	Uppper Cliff, Alabama	Medium Volatile Bituminous	✥
#18	Rosa, Alabama	Medium Volatile Bituminous	∩
#19	Black Creek, Alabama	Medium Volatile Bituminous	⬡
#20	Hardin, Montana	Subbituminous	◁
#21	Lema, Colorado	High Volatile C Bituminous	⊳

A-1 (Continued)

Designation	Location	Coal	Symbol
#22	Waylaun, Ky.	High Volatile A Bituminous	⌘
#23	Upshur, W. Va.	High Volatile A Bituminous	◿
#24	Gauley Eagle, W. Va.	High Volatile A Bituminous	⬭
#25	Meigs, Ohio	High Volatile C Bituminous	⊕
#26	Ridge 5, Ohio	High Volatile A Bituminous	⊠
#27	Martinka, Ohio	High Volatile A Bituminous	◈
#28	Coalburg, Ohio	High Volatile A Bituminous	⌂
#29	Beach Bottom, Ohio	High Volatile A Bituminous	⟠
#30	Freeport, Ohio	High Volatile B Bituminous	⊗
#31	Muskingum, Ohio	High Volatile B Bituminous	◇
#32	Hazelton, PA.	Anthracite	◗
#33	Providence, Ky.	High Volatile A Bituminous	⊗
#34	Holden (Kite), W. Va.	High Volatile A Bituminous	▽
#35	Holden (Welco), W. Va.	High Volatile A Bituminous	◁
#36	Lyons, Va.	High Volatile A Bituminous	⊖
#37	Splash Dam, Va.	High Volatile A Bituminous	⊖
#39	Shell, Texas	Subbituminous C	◖
#44	Acurex Char		⊗
#45	Acurex Coal	Bituminous	⊘
#2A	Four Corners, N.M.	Bituminous	⦶
#46	Loy-Yang		◣
#47	YALLOURN		◢
#48	Morwell		◤
#49	Germany	Saar Bituminous	

A-2

SUMMARY OF MINES FROM WHICH COALS WERE OBTAINED

Coal No.	Coal	Address
1	Colstrip	Long Construction Colstrip, Montana
2	Farmington	Western Coal Company Box 509 Farmington, New Mexico
3	Fruitland	Arizona Public Service Comapny Box 355 Fruitland, New Mexico
4	Scranton	Knife River Coal Company NAS Scranton, North Dakota
5	Kemmerer	Kemmerer Coal Kemmerer, Wyoming
6	Beulah	Knife River Coal Mining Company Beulah, North Dakota
7	Colorado Coal	Unknown
8	Hardin	Commercial Testing and Engineering 30 M E of Hardin, Montana
9	Beulah	North AM Coal Corporation Beulah, North Dakota
10	Velva	Consolidated Coal Company Velva, North Dakota
11	Montana Savage #11	Knife River Coal Company Savage, Montana
12	Paonia, Colorado	Colorado Westmoreland Box E Paonia, Colorado
13A	Cadiz, OH-13A	Consolidation Coal Company Cadiz, Ohio

A-2 (Continued)

SUMMARY OF MINES FROM WHICH COALS WERE OBTAINED

Coal No.	Coal	Address
13B	Cadiz	Consolidation Coal Company Cadiz, Ohio
14	Buffalo Mark	Buffalo Mining Company Division of Pittson Lynchburg, West Virginia
15	Elkay	Elkay Mining Company West Virginia
16	Sewanee	Mid-South Fuel Sales Box 327 Oneonta, Alabama
17	Upper Cliff	
18	Rosa	
19	Black Creek	Calvert & Marsh Coal Company Route 1 Oneonta, Alabama 35121
20	Hardin	Westmoreland Resources Box 449 Hardin, Montana
21	Lema	Island Creek Coal Sales Company 8301 E. Prentice Englewood, Colorado
22	Wayland	National Mine Corporation Wayland, Kentucky
23	Upshur,Lower Kittanning Seam	Island Creek Coal Company Craigsville, West Virginia 26205

A-2 (Continued)

SUMMARY OF MINES FROM WHICH COALS WERE OBTAINED

Coal No.	Coal	Address
24	Gauley, Eagle #4 Kittanning Seam	Island Creek Coal Company Craigsville, West Virginia 26205
25	Meigs-Clarion 4A Seam	Southern Ohio Coal Company Meigs Mine Langsville, Ohio
26	Ridge 5 Mine Lower Kittanning 5-Block Seam	Cedar Coal Company Ridge 5 Mine
27	Martinka Lower Kittanning 5-Block Seam	Southern Ohio Coal Company Martinka #1 Mine Langsville, Ohio
28	Coalburg #1 Mine Central Appalachian	Central Appalachian Coal Company Coalburg #1 Mine
29	Beech Bottom Pittsburg #8 Seam	Windsor Power House Coal Company Beech Bottom Mine Company
30	Freeport Lower Freeport Seam	Southern Appalachian Coal Company Freeport Mines
31	Muskingum Meigs Creek #9 Seam	Central Ohio Coal Company Muskingum Mine
32	Anthracite-Hazelton	Beltrami Enterprises Hazelton, PA (717) 459-1491
33	Providence #1 Mine #9 Seam	Island Creek Coal Company West Kentucky Division Providence, Kentucky
34	Kite-Elkhorn	Island Creek Coal Company Holden, West Virginia

A-2 (Concluded)

SUMMARY OF MINES FROM WHICH COALS WERE OBTAINED

Coal No.	Mine	Address
35	Welco-Elkhorn 3	Island Creek Coal Company Holden, West Virginia
36	Lyons	Virginia Iron, Coal, and Coke Coeburn, Virginia
37	Splash Dam	Virginia Iron, Coal, and Coke Coeburn, Virginia
38		Beltrani Enterprises Hazelton, PA
39	Texas Lignite	Shell Development Corporation 3333 Hwy 6 South Houston, Texas 77082

A-3

Forms of Sulfur Present in Coals Available for Testing at EER

Fuel	% Sulfur (Dry)			
	Total	Pyritic	Organic	Sulfate
Western Kentucky	3.21	0.78	1.71	0.72
TRW #1	1.02	0.30	0.52	0.20
TRW #2	0.86	0.14	0.66	0.06
TRW #3	3.46	1.21	1.79	0.46
Utah - I	0.66	0.08	0.53	0.05
Utah - II	0.76	0.14	0.62	0.00
Colstrip #1	0.63	0.27	0.36	0.00
Farmington #2	0.81	0.30	0.51	0.51
Four Corners #2A				
Fruitland #3	0.93	0.28	0.56	0.09
Scranton #4	1.52	0.49	1.00	0.03
Kennerer #5	0.61	0.13	0.48	0.00
Beulah #6	1.14	0.53	0.58	0.03
Colorado #7	2.45	1.76	0.63	0.06
Hardin #8	0.79	0.47	0.32	0.00
Beulah #9	0.37	0.04	0.33	0.00
Velva #10	0.52	0.11	0.38	0.00
Savage #11	0.42	0.02	0.40	0.00
Paonia #12	0.41	0.02	0.39	0.00
Cadiz #13A	2.57	1.48	2.00	0.09
Cadiz #13B	7.40	6.00	1.09	0.31
Buffalo Mark #14	1.59	0.89	0.70	0.00
Elkay #15	2.47	1.60	0.82	0.05
Sewanee #16	0.77	0.25	0.46	0.06
Upper Cliff #17	1.30	0.52	0.61	0.17
Rosa #18	1.04	0.47	0.50	0.07
Black Creek #19	0.76	0.07	0.69	0.00
Hardin #20	1.07	0.70	0.37	0.00
Lema #21	0.60	0.18	0.40	0.02

A-3 (Continued)

Forms of Sulfur Present in Coals Available for Testing at EER

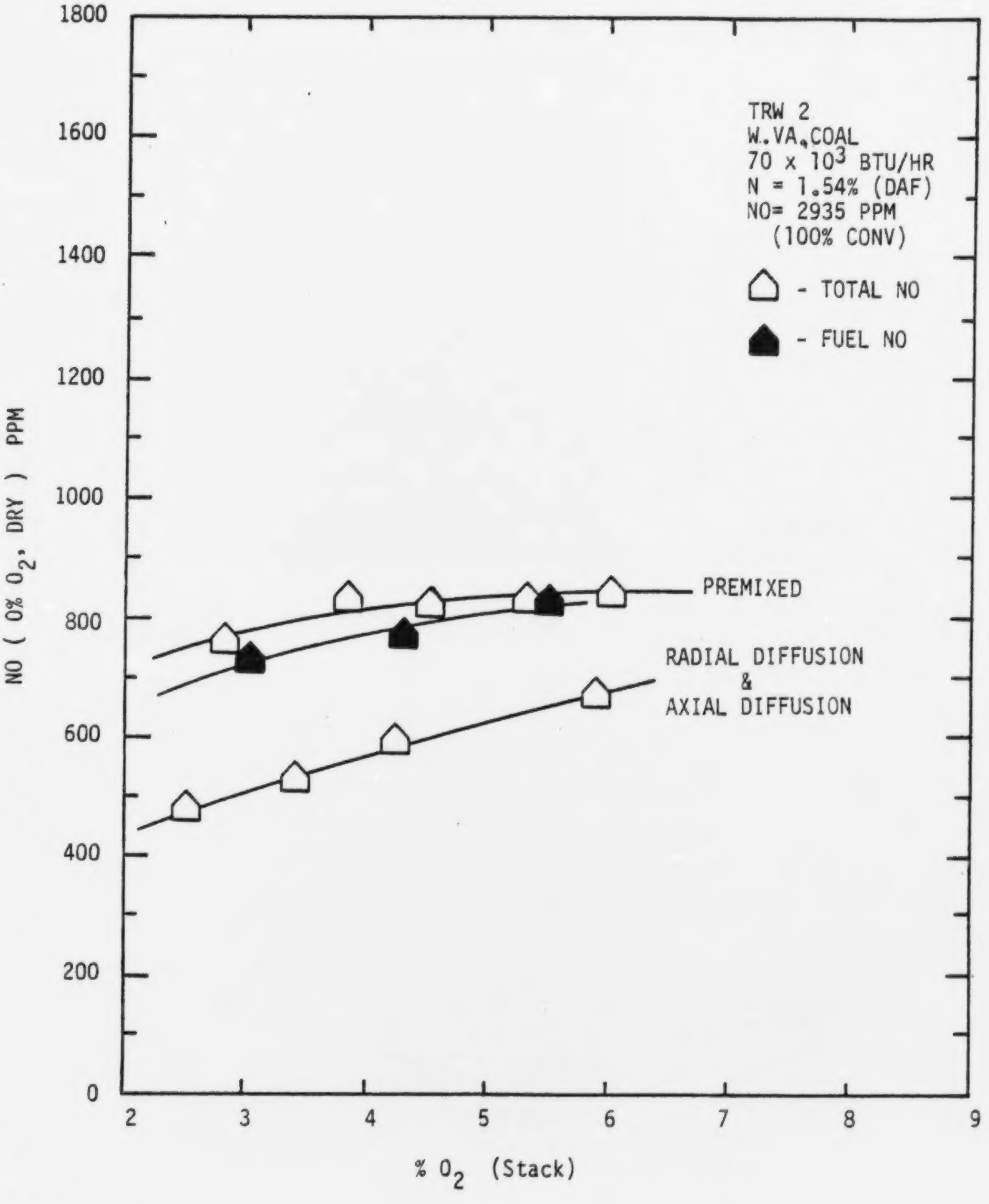
Fuel	% Sulfur (Dry)			
	Total	Pyritic	Organic	Sulfate
Waylaun #22	0.83	0.21	0.62	0.00
Upshur #23	1.09	0.32	0.67	0.10
Gauley Eagle #24	0.84	0.30	0.54	0.00
Meigs #25	4.79	3.14	0.47	0.18
Ridge #26	1.00	0.41	0.59	0.00
Martinka #27	3.16	2.63	0.53	0.00
Coalburg #28	0.53	0.05	0.40	0.00
Beech Bottom #29	2.94	2.5	0.73	0.06
Freeport #30	1.00	0.65	0.33	0.02
Muskwggum #31	6.51	3.77	2.66	0.08
Anthracite #32	0.59	0.12	0.47	0.00
Providence #33	4.08	2.33	0.71	0.04
Holden (Kite) #34	0.83	0.24	0.59	0.00
Holden (Welco) #35	0.91	0.26	0.65	0.00
Lyons #36	1.85	0.93	0.70	0.22
Splash #37	1.53	0.97	0.56	0.00
Texas #39	1.02	0.16	0.86	0.00
Acurex Char #44				
Acurex Colal #45				
Loy-Yang #46				
Yallourn # 47				
Morwell #48				

APPENDIX B

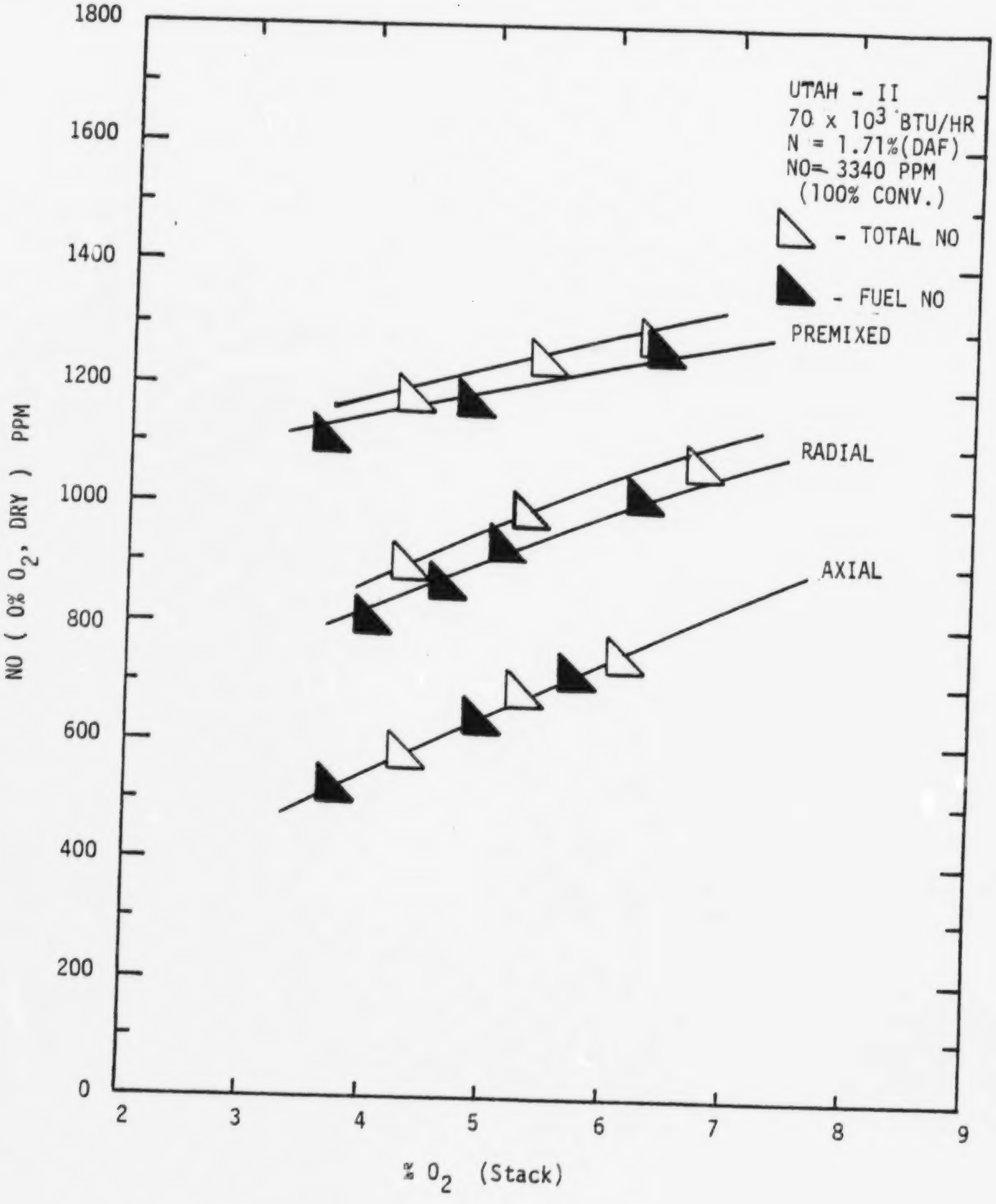
Summary of Bench-Scale Data

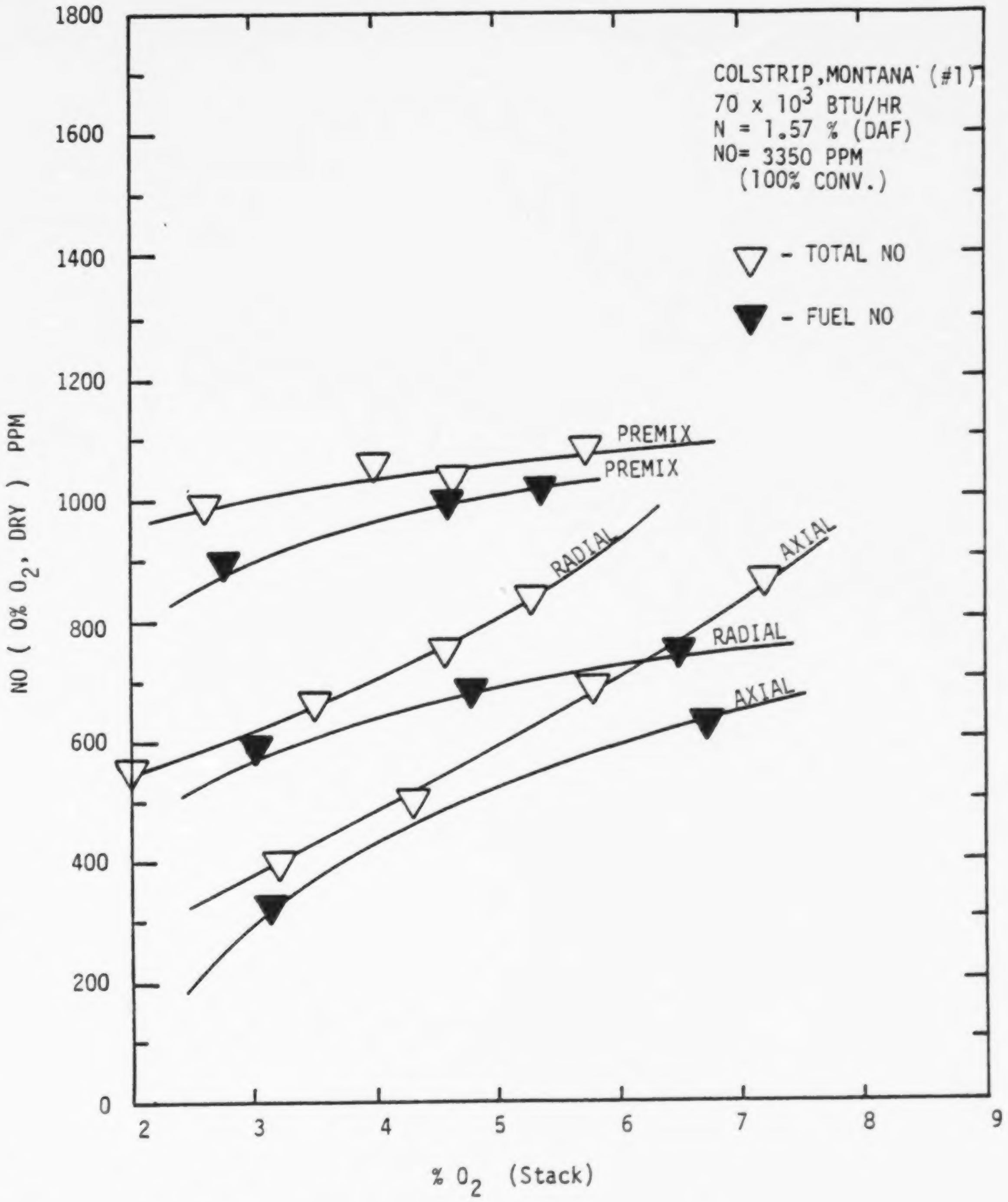
Fuel and Thermal NO_x Emissions as a Function of Excess Air and Burner Type

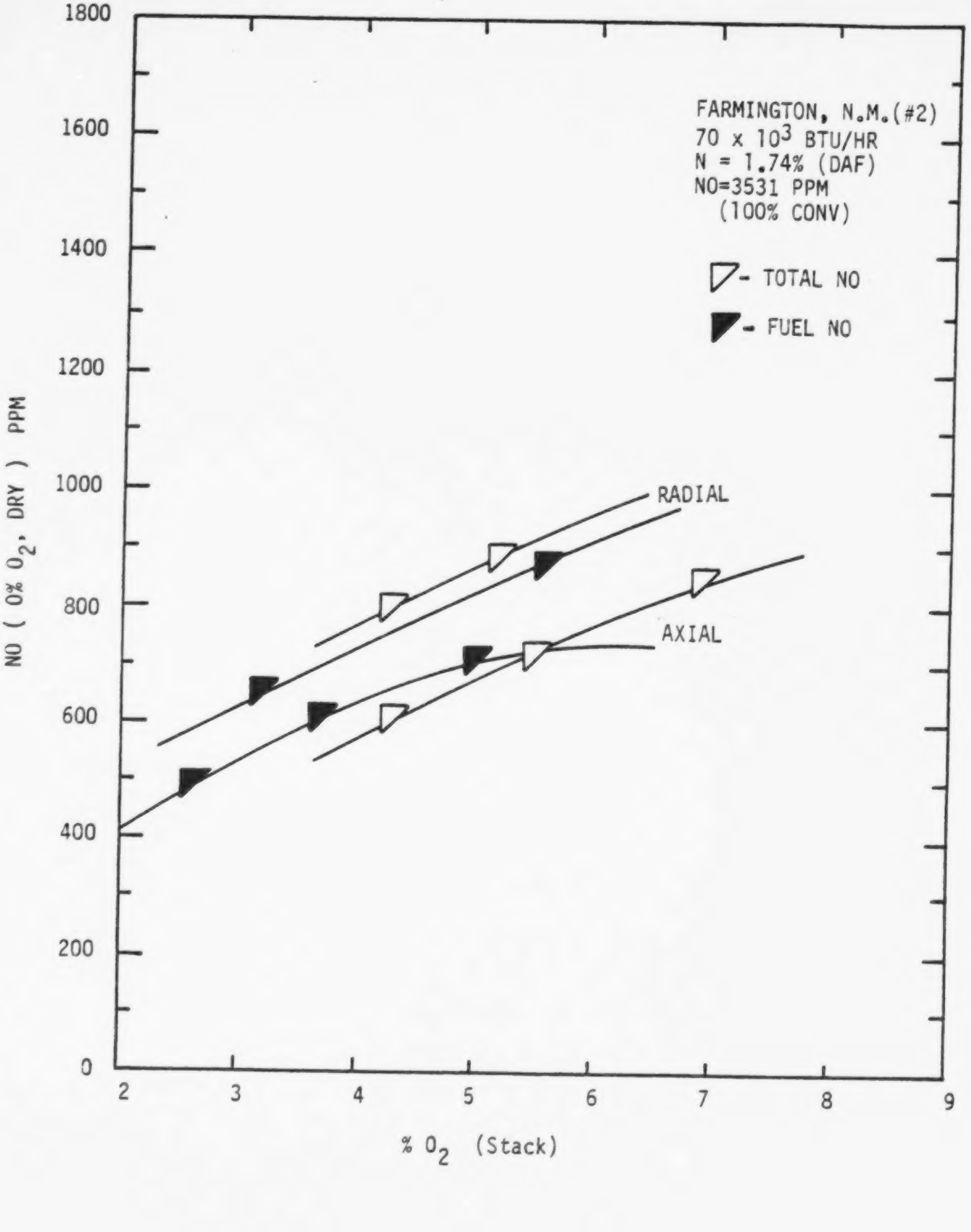
	Page
TRW 2, W.V.	B-2
Utah II	B-3
Colstrip, Montana No. 1	B-4
Farmington, N.M. No. 2	B-5
Four Corners, N.M. No. 2A	B-6
Fruitland, N.M. No. 3	B-7
Scranton, N.D. No. 4	B-8
Beulah, N.D. No. 6	B-9
Hardin, Montana No. 8	B-10
Beulah, N.D. No. 9	B-11
Savage, Montana No. 11	B-12
Cadiz, Ohio No. 13B	B-13
Elkay, W.V. No. 15	B-14
Upper Cliff, Alabama No. 17	B-15
Rosa, Alabama No. 18	B-16
Black Creek, Alabama No. 19	B-17
Hardin, Montana No. 20	B-18
Gauley Eagle, W.V. No. 24	B-19
Penn. Anthracite No. 32	B-20
Texas Lignite No. 39	B-21
Acurex, Utah Char No. 44	B-22
Acurex, Utah Coal No. 45	B-23
Morwell, Aus. No. 48	B-24
Utah I	B-25

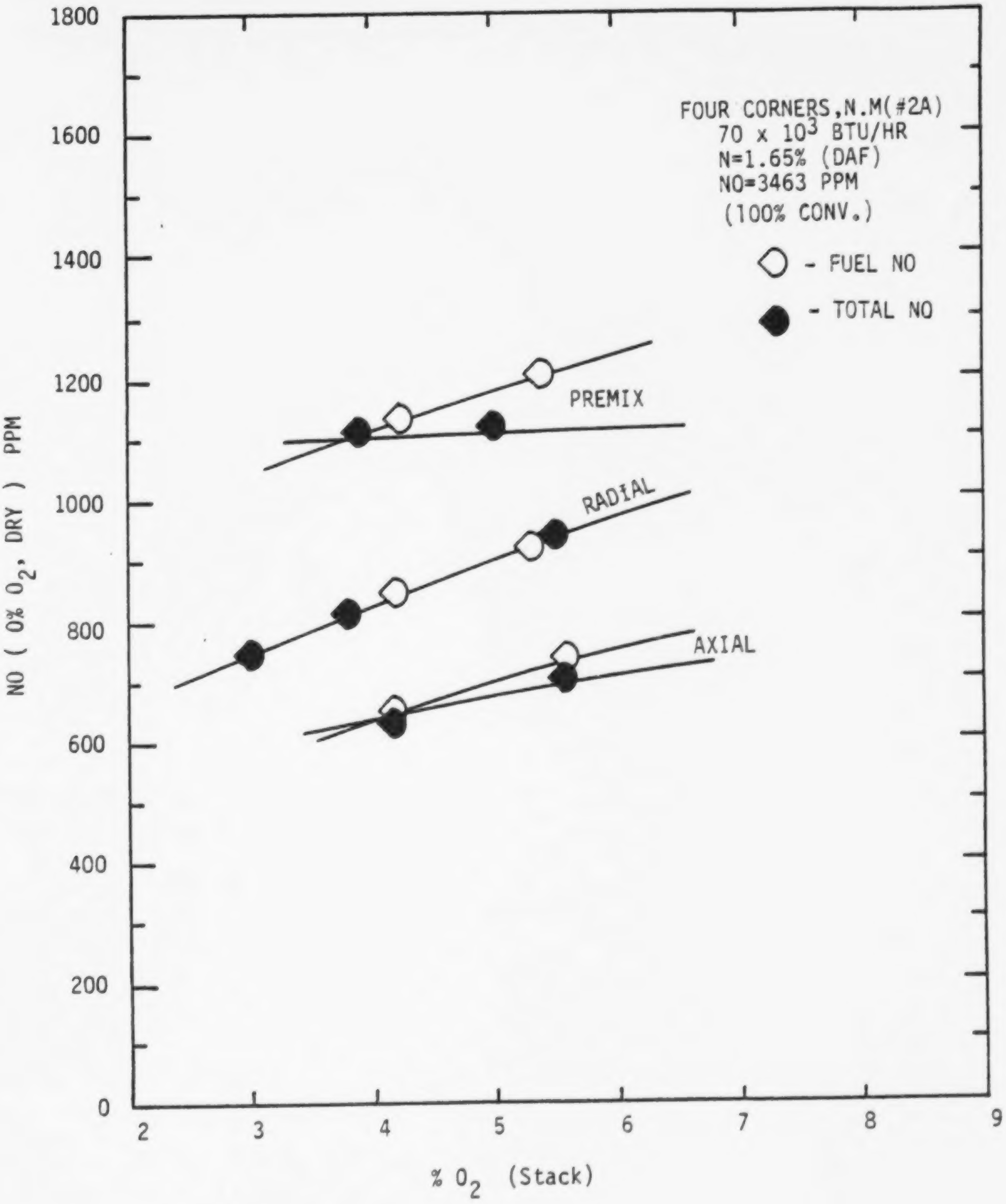


1800
1600
1400
1200
1000
800
600
400
200
0
2
3
4
5
6
7
8
9
NO (0% O_2, DRY) PPM
% O_2 (Stack)
TRW 2
W. VA. COAL
70 x 10^3 BTU/HR
N = 1.54% (DAF)
NO= 2935 PPM
(100% CONV)
△ - TOTAL NO
▲ - FUEL NO
PREMIXED
RADIAL DIFFUSION
&
AXIAL DIFFUSION

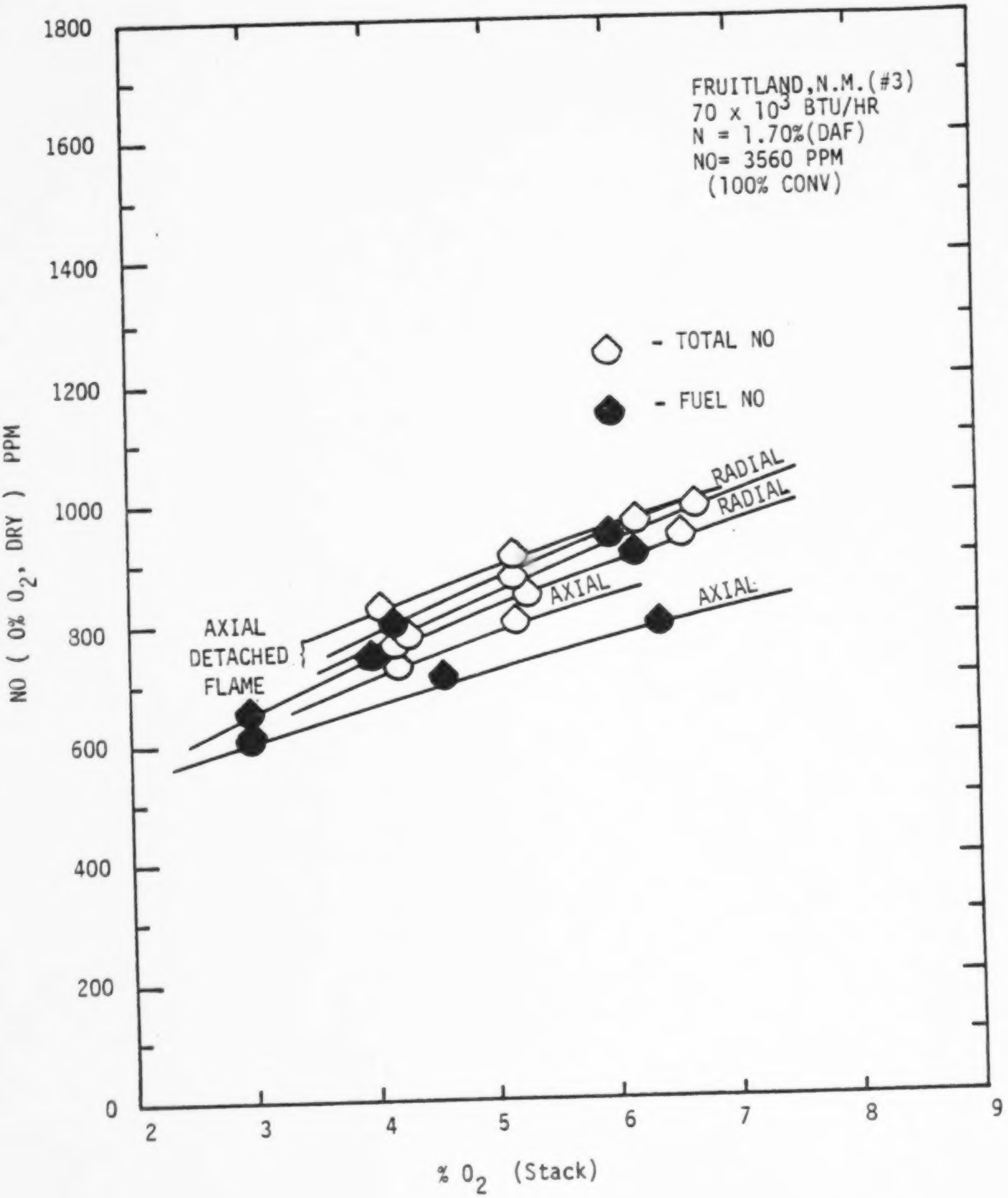

UTAH - II
70 x 10^3 BTU/HR
N = 1.71%(DAF)
NO= 3340 PPM
(100% CONV.)
△ - TOTAL NO
◣ - FUEL NO
PREMIXED
RADIAL
AXIAL
NO (0% O2, DRY) PPM
0
200
400
600
800
1000
1200
1400
1600
1800
2
3
4
5
6
7
8
9
% O2 (Stack)

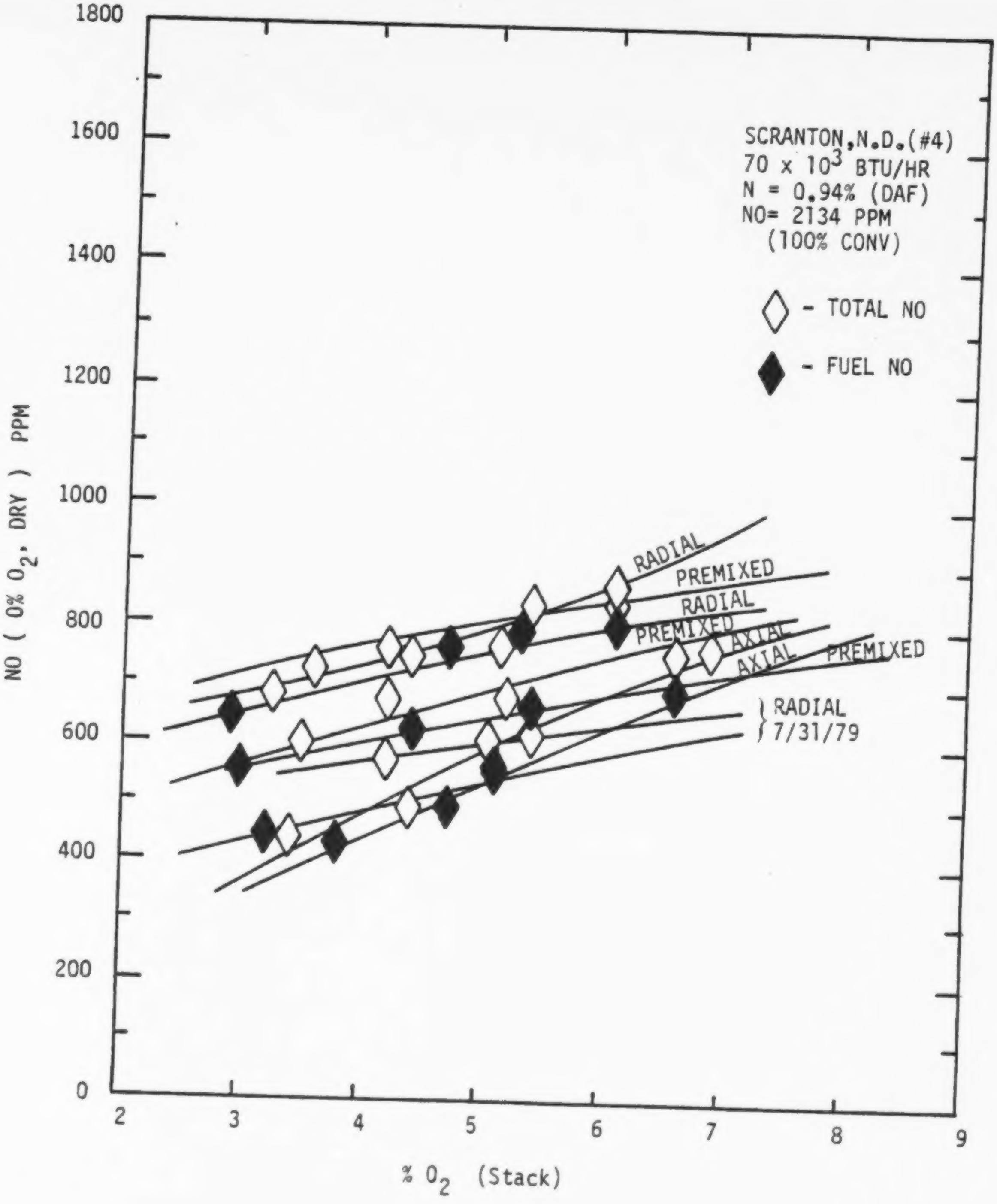

COLSTRIP, MONTANA (#1)
70 x 10^3 BTU/HR
N = 1.57 % (DAF)
NO= 3350 PPM
(100% CONV.)
▽ - TOTAL NO
▼ - FUEL NO
PREMIX
PREMIX
RADIAL
RADIAL
AXIAL
AXIAL
NO (0% O_2, DRY) PPM
1800
1600
1400
1200
1000
800
600
400
200
0
2
3
4
5
6
7
8
9
% O_2 (Stack)


1800
1600
1400
1200
1000
800
600
400
200
0
NO (0% O_2, DRY) PPM
2
3
4
5
6
7
8
9
% O_2 (Stack)
FARMINGTON, N.M.(#2)
70 x 10^3 BTU/HR
N = 1.74% (DAF)
NO=3531 PPM
(100% CONV)
▽- TOTAL NO
▼- FUEL NO
RADIAL
AXIAL

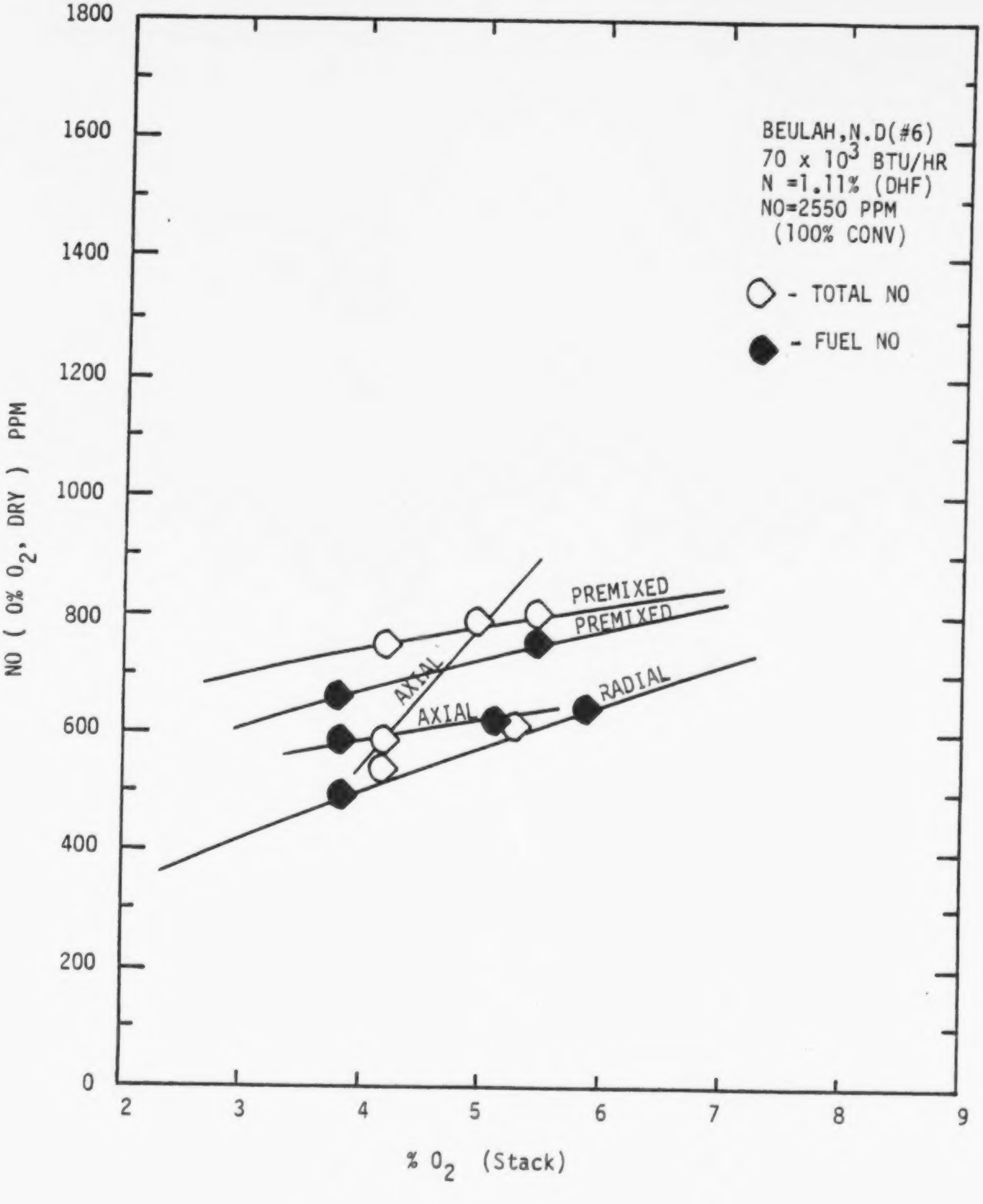


1800
1600
1400
1200
1000
800
600
400
200
0
NO (0% O_2, DRY) PPM
2
3
4
5
6
7
8
9
% O_2 (Stack)
FOUR CORNERS,N.M(#2A)
70 x 10^3 BTU/HR
N=1.65% (DAF)
NO=3463 PPM
(100% CONV.)
○ - FUEL NO
● - TOTAL NO
PREMIX
RADIAL
AXIAL

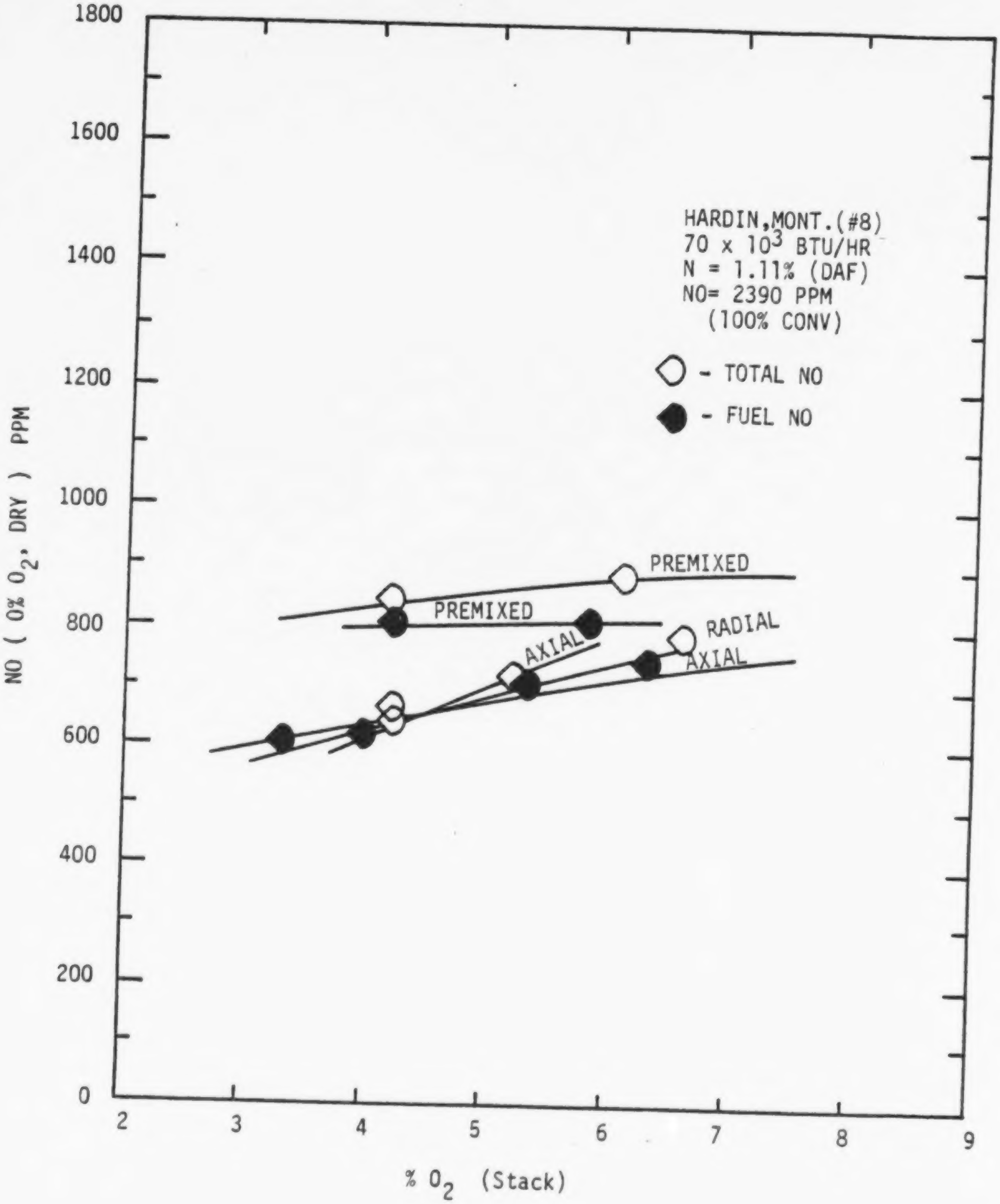

1800
1600
1400
1200
1000
800
600
400
200
0
2
3
4
5
6
7
8
9
NO (0% O_2, DRY) PPM
% O_2 (Stack)
FRUITLAND,N.M.(#3)
70 x 10^3 BTU/HR
N = 1.70%(DAF)
NO= 3560 PPM
(100% CONV)
○ - TOTAL NO
● - FUEL NO
RADIAL
RADIAL
AXIAL
AXIAL
AXIAL
DETACHED
FLAME

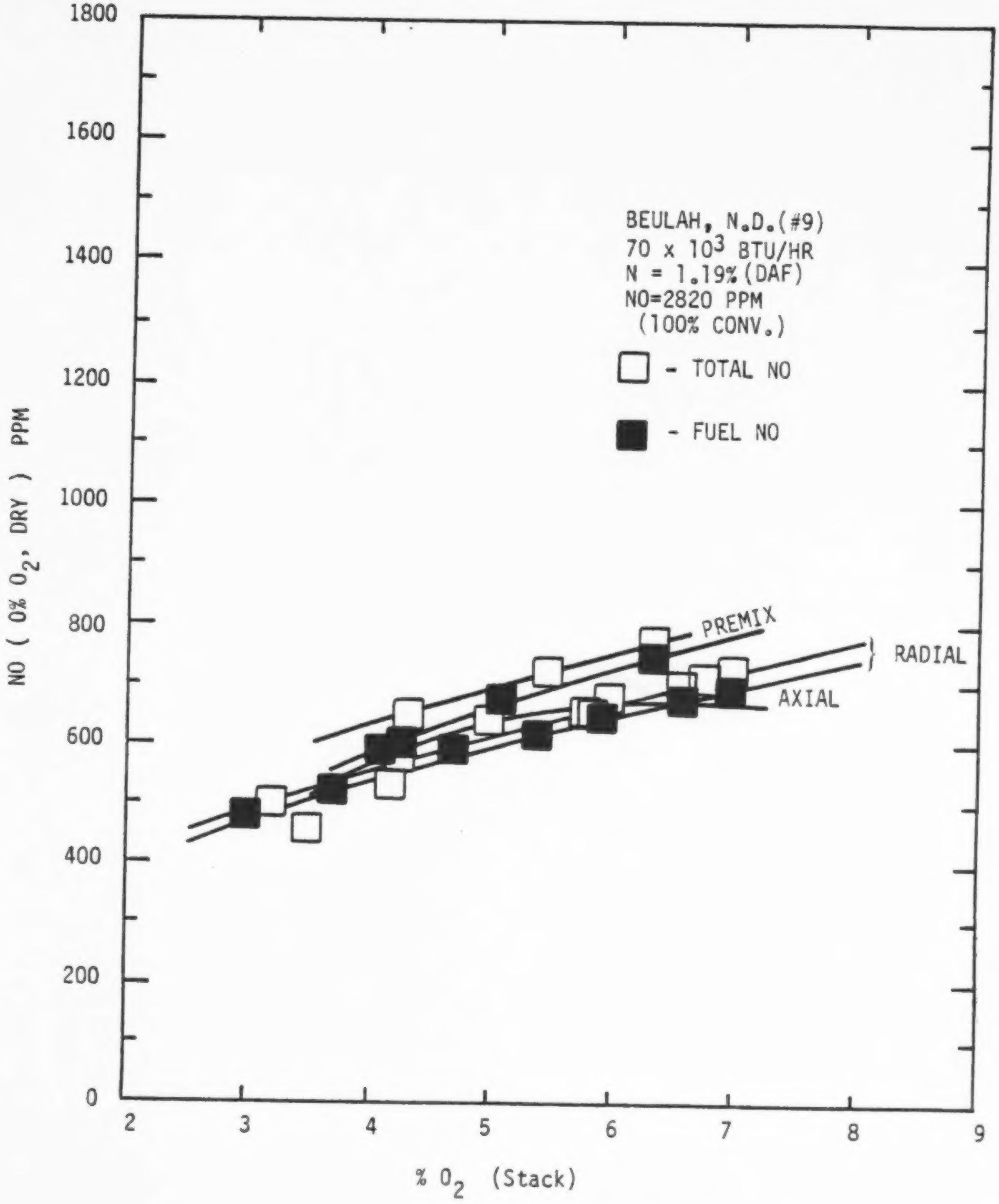


SCRANTON,N.D.(#4)
70 x 10³ BTU/HR
N = 0.94% (DAF)
NO= 2134 PPM
(100% CONV)
◇ - TOTAL NO
◆ - FUEL NO
RADIAL
PREMIXED
RADIAL
PREMIXED
AXIAL
AXIAL
PREMIXED
RADIAL
7/31/79
NO (0% O2, DRY) PPM
% O2 (Stack)
0
200
400
600
800
1000
1200
1400
1600
1800
2
3
4
5
6
7
8
9



1800
1600
1400
1200
1000
800
600
400
200
0
2
3
4
5
6
7
8
9
NO (0% O_2, DRY) PPM
% O_2 (Stack)
BEULAH,N.D(#6)
70 x 10^3 BTU/HR
N =1.11% (DHF)
NO=2550 PPM
(100% CONV)
○ - TOTAL NO
● - FUEL NO
PREMIXED
PREMIXED
AXIAL
AXIAL
RADIAL


1800
1600
1400
1200
1000
800
600
400
200
0
2
3
4
5
6
7
8
9
NO (0% O_2, DRY) PPM
% O_2 (Stack)
HARDIN, MONT. (#8)
70 x 10^3 BTU/HR
N = 1.11% (DAF)
NO= 2390 PPM
(100% CONV)
○ - TOTAL NO
● - FUEL NO
PREMIXED
PREMIXED
AXIAL
RADIAL
AXIAL



1800
1600
1400
1200
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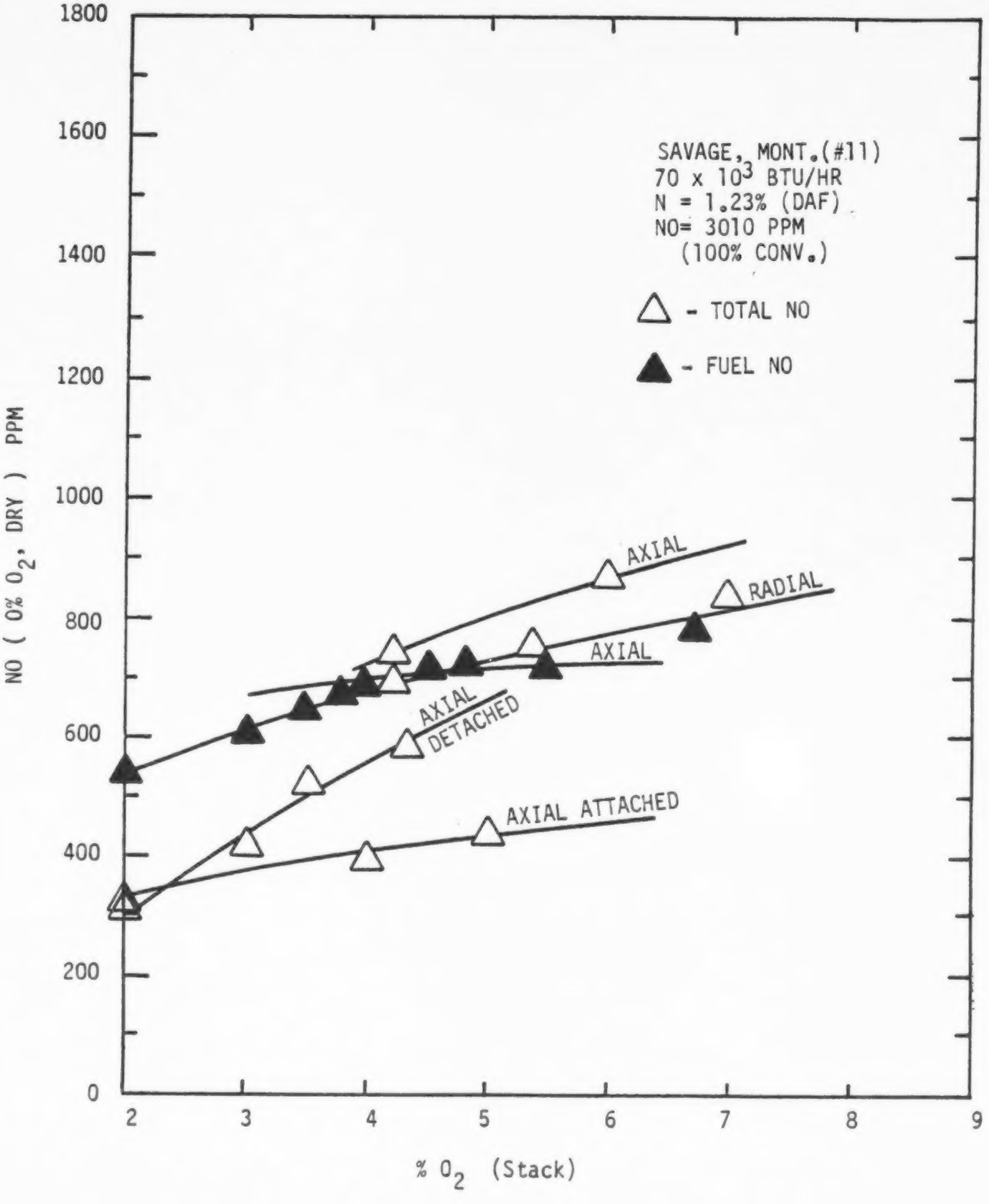
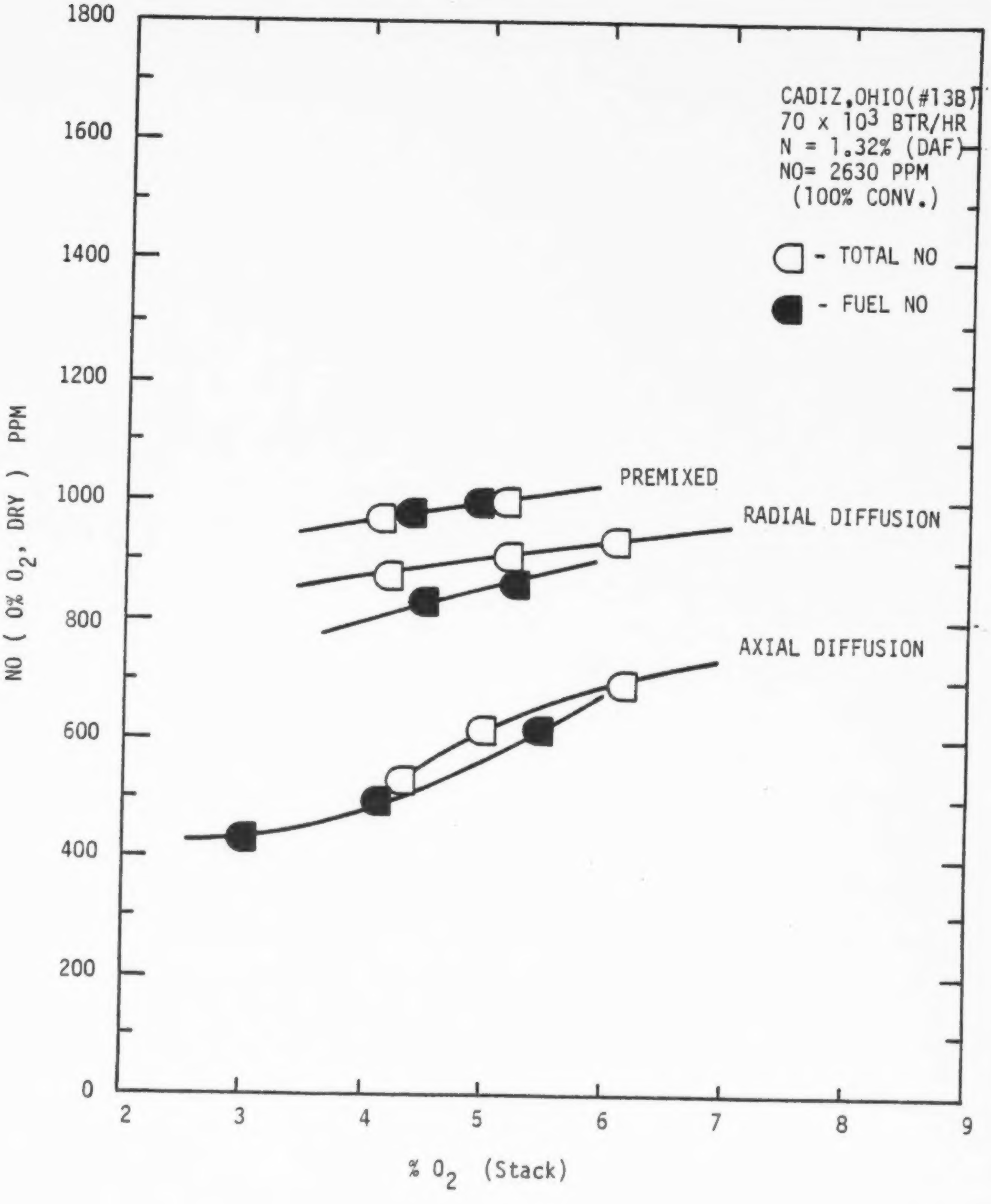
600
400
200
0
NO (0% O_2, DRY) PPM
2
3
4
5
6
7
8
9
% O_2 (Stack)
BEULAH, N.D.(#9)
70 x 10^3 BTU/HR
N = 1.19% (DAF)
NO=2820 PPM
(100% CONV.)
☐ - TOTAL NO
■ - FUEL NO
PREMIX
RADIAL
AXIAL


SAVAGE, MONT.(#11)
70 x 10^3 BTU/HR
N = 1.23% (DAF)
NO= 3010 PPM
(100% CONV.)
△ - TOTAL NO
▲ - FUEL NO
AXIAL
RADIAL
AXIAL
AXIAL DETACHED
AXIAL ATTACHED
NO (0% O_2, DRY) PPM
0
200
400
600
800
1000
1200
1400
1600
1800
2
3
4
5
6
7
8
9
% O_2 (Stack)


CADIZ,OHIO(#13B)
70 x 10³ BTR/HR
N = 1.32% (DAF)
NO= 2630 PPM
(100% CONV.)
◯ - TOTAL NO
● - FUEL NO
PREMIXED
RADIAL DIFFUSION
AXIAL DIFFUSION
NO (0% O2, DRY) PPM
% O2 (Stack)
1800
1600
1400
1200
1000
800
600
400
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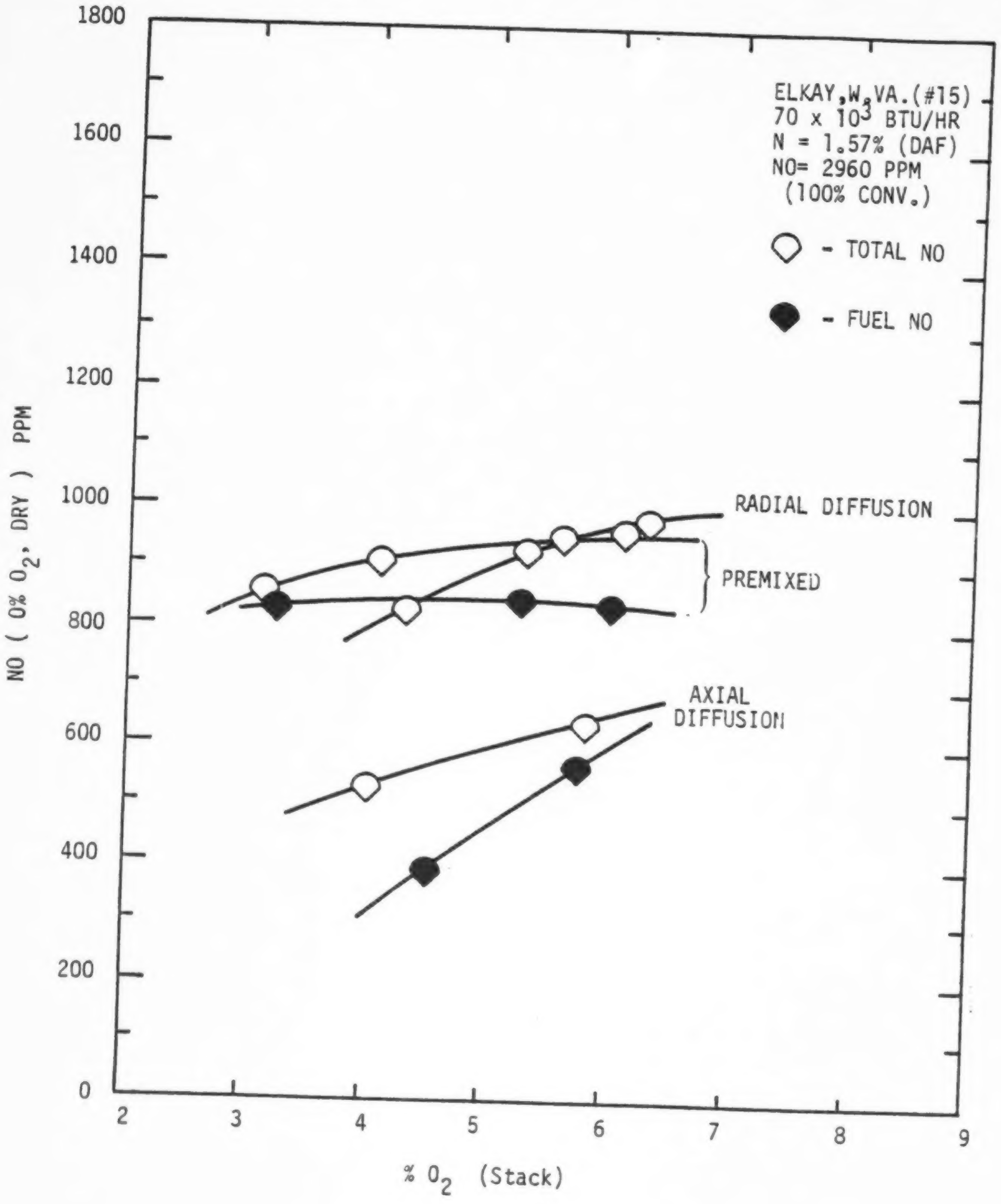
9


ELKAY,W.VA.(#15)
70 x 10^3 BTU/HR
N = 1.57% (DAF)
NO= 2960 PPM
(100% CONV.)
○ - TOTAL NO
● - FUEL NO
RADIAL DIFFUSION
PREMIXED
AXIAL DIFFUSION
NO (0% O_2, DRY) PPM
1800
1600
1400
1200
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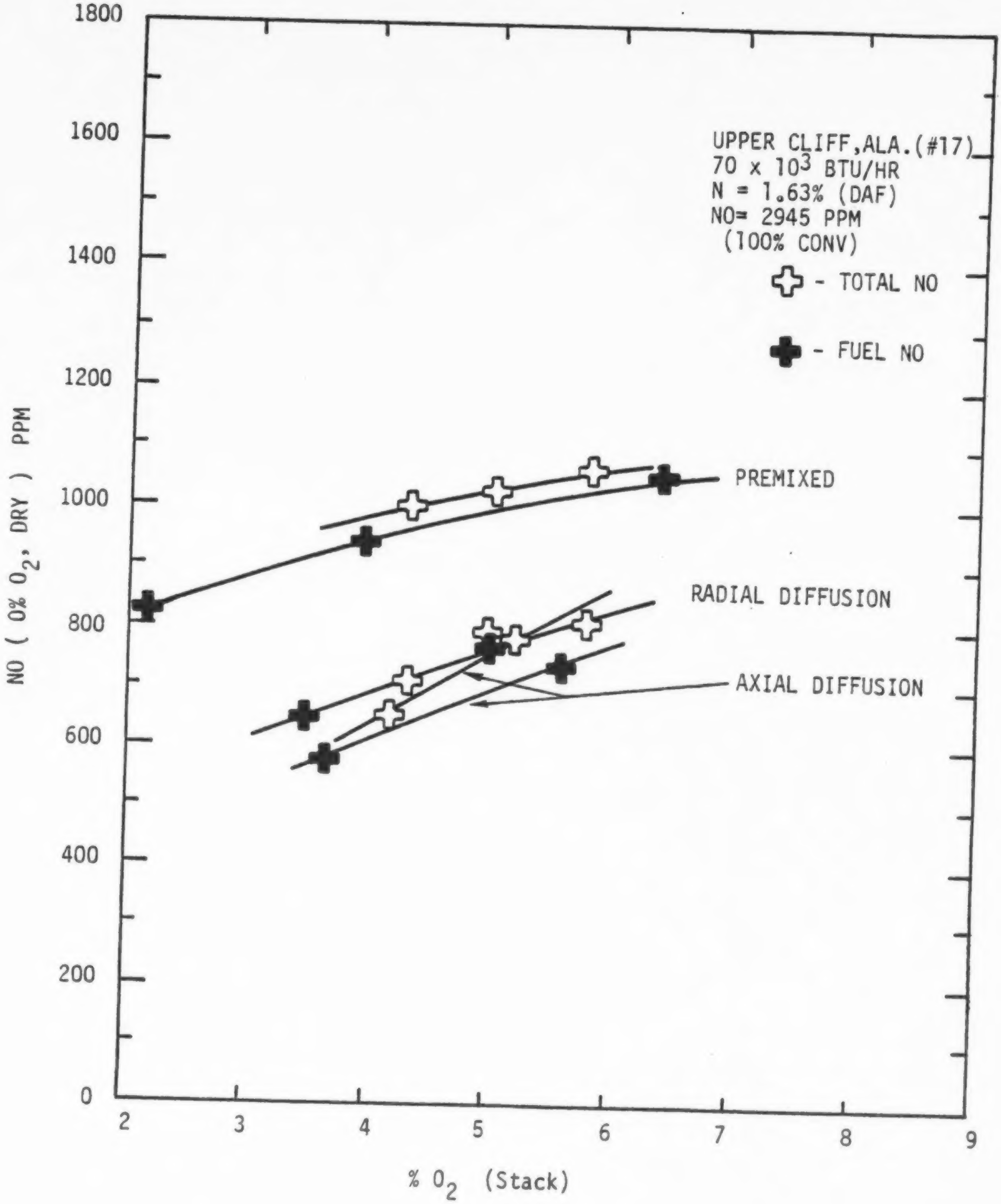
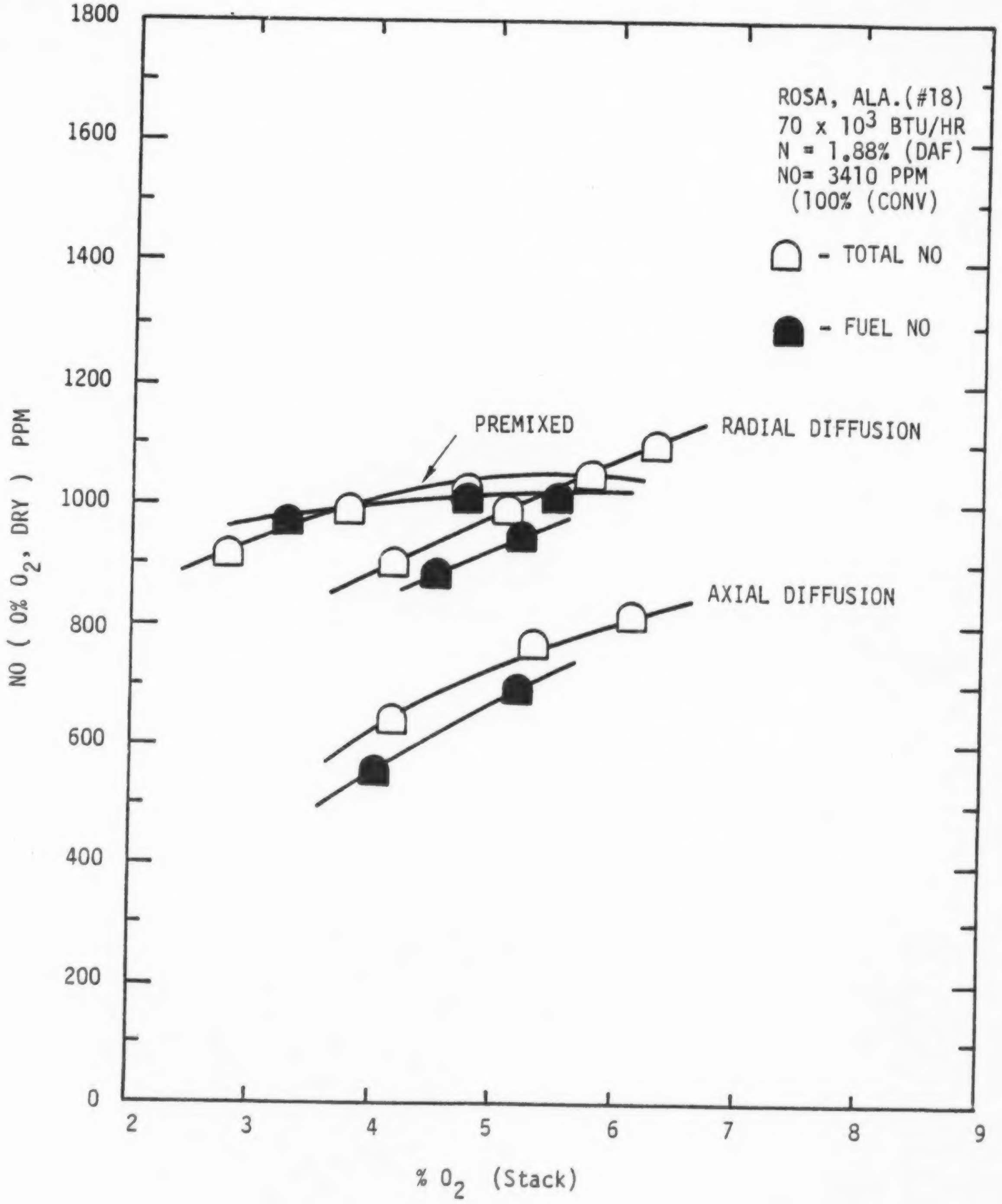
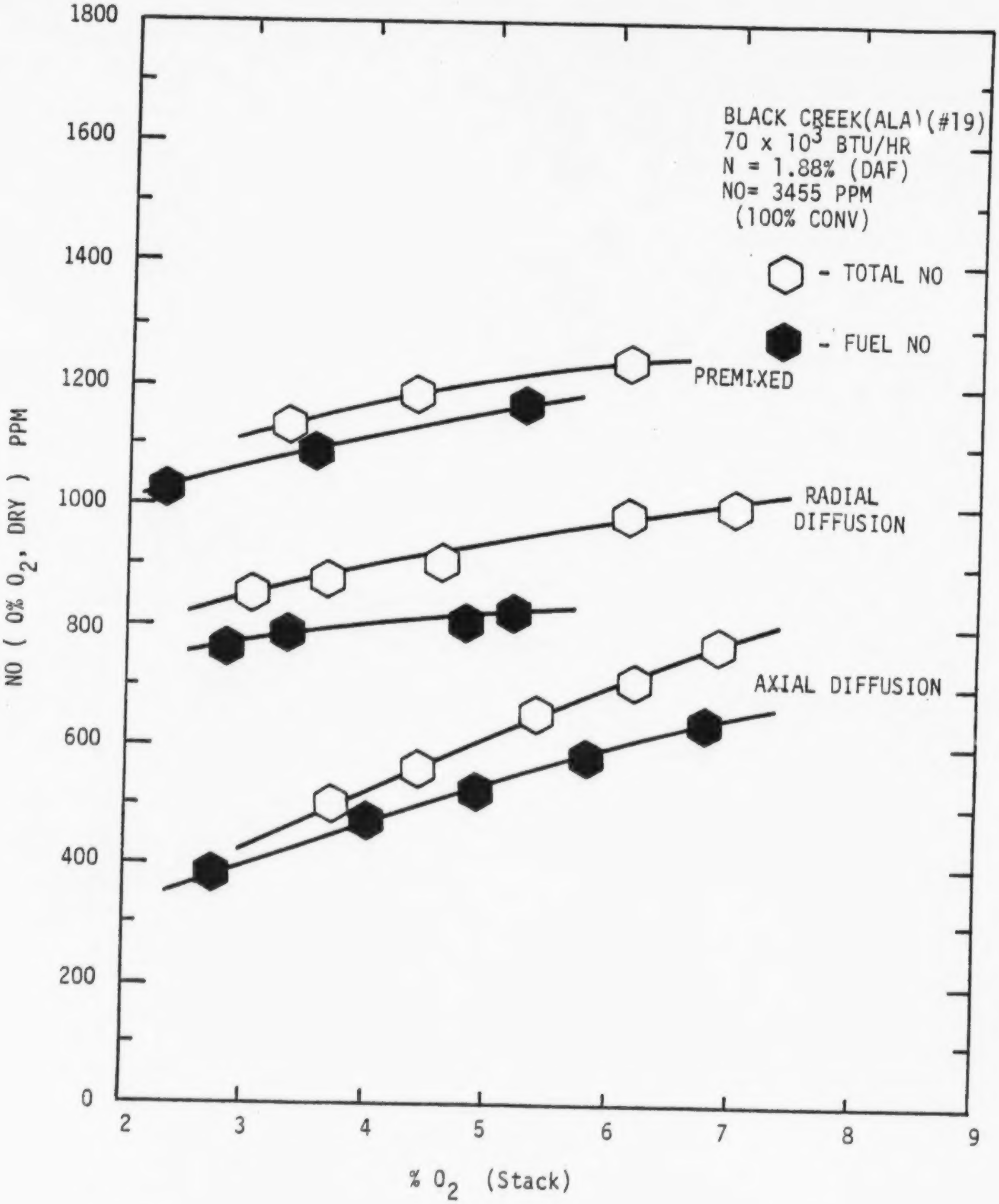
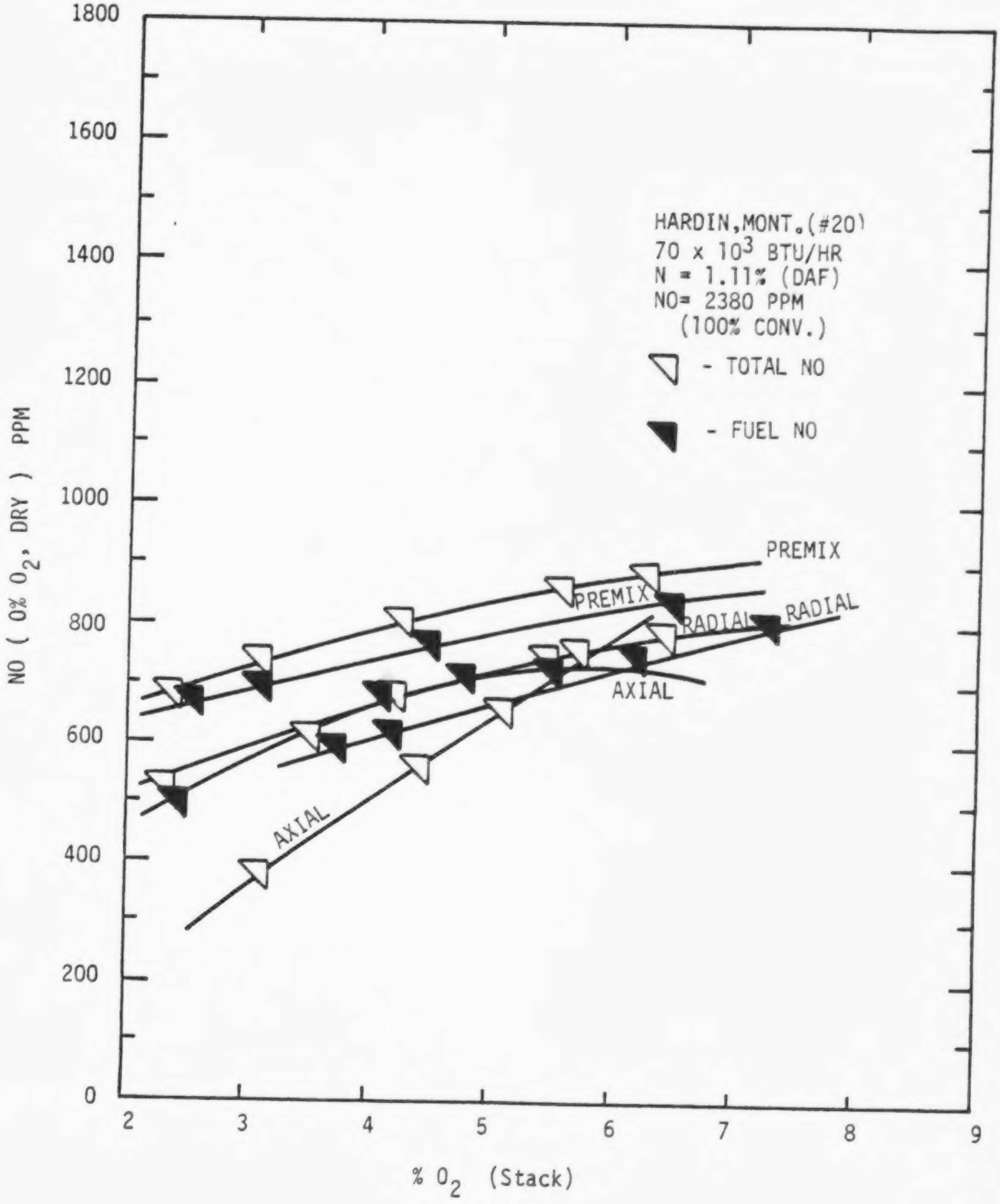
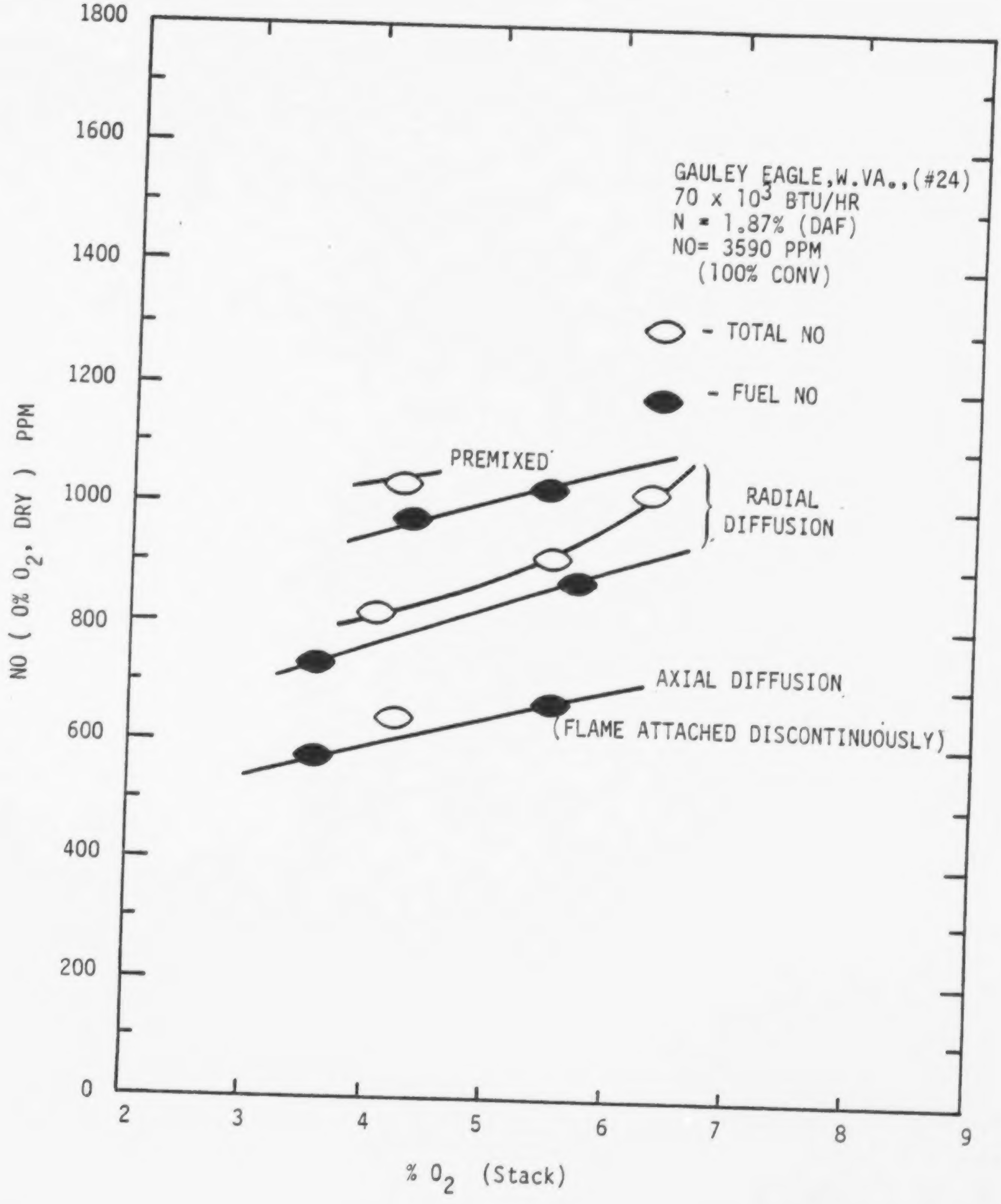
800
600
400
200
0
2
3
4
5
6
7
8
9
% O_2 (Stack)

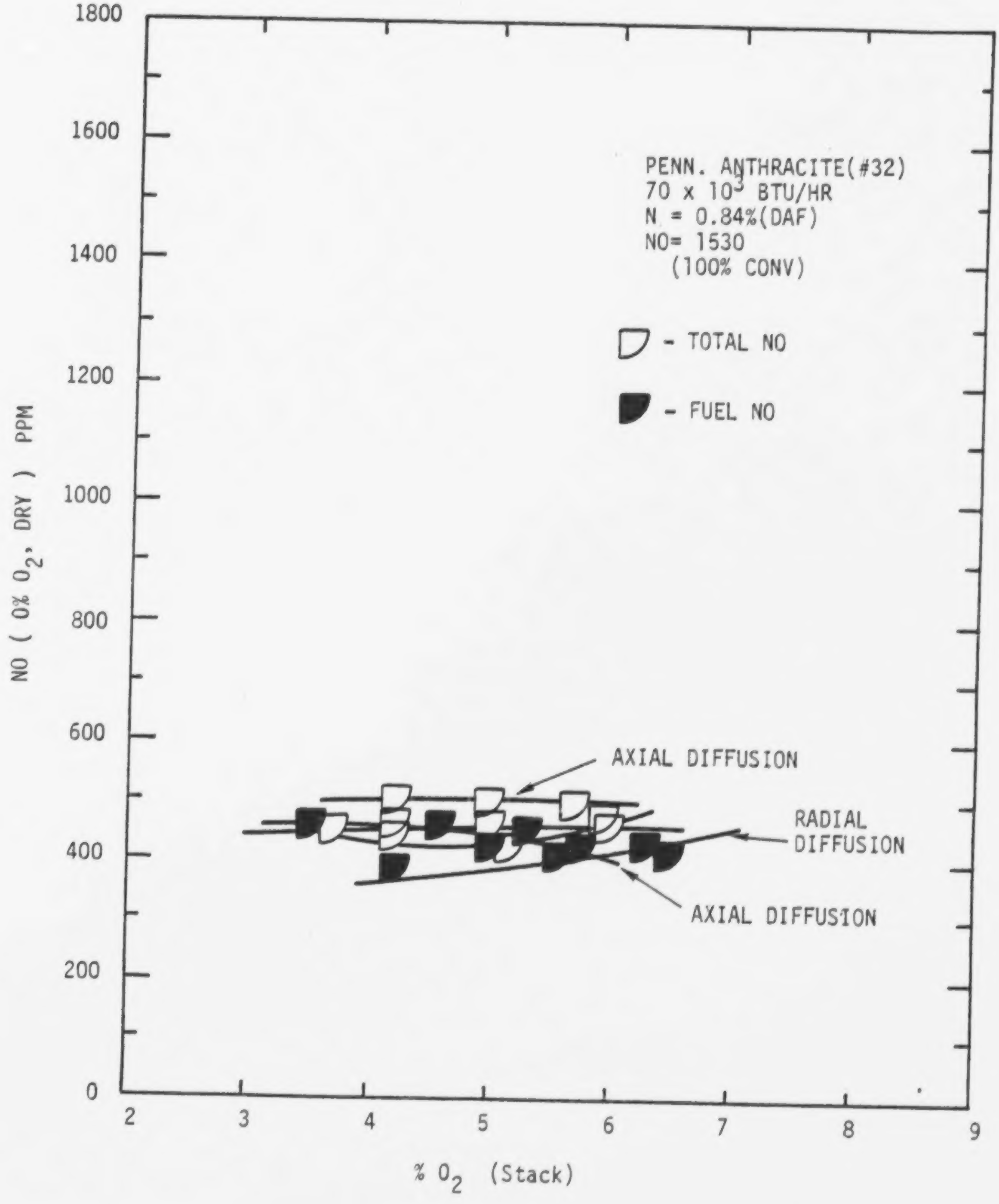

UPPER CLIFF,ALA.(#17)
70 x 10³ BTU/HR
N = 1.63% (DAF)
NO= 2945 PPM
(100% CONV)
✚ - TOTAL NO
✚ - FUEL NO
PREMIXED
RADIAL DIFFUSION
AXIAL DIFFUSION
NO (0% O₂, DRY) PPM
% O₂ (Stack)
0
200
400
600
800
1000
1200
1400
1600
1800
2
3
4
5
6
7
8
9

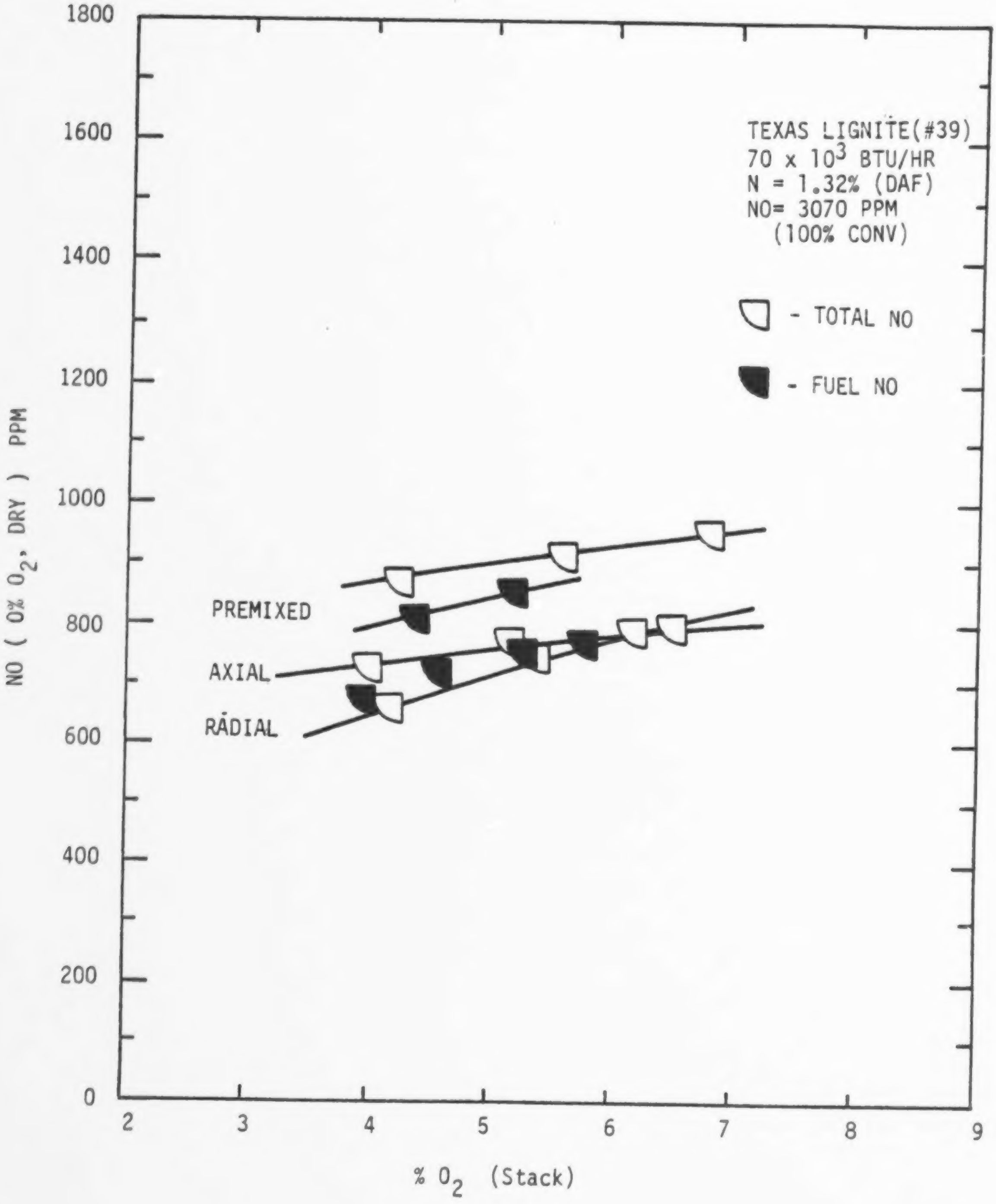

1800
1600
1400
1200
1000
800
600
400
200
0
NO (0% O_2, DRY) PPM
2
3
4
5
6
7
8
9
% O_2 (Stack)
ROSA, ALA.(#18)
70 x 10^3 BTU/HR
N = 1.88% (DAF)
NO= 3410 PPM
(100% (CONV)
- TOTAL NO
- FUEL NO
PREMIXED
RADIAL DIFFUSION
AXIAL DIFFUSION


BLACK CREEK(ALA)(#19)
70 x 10^3 BTU/HR
N = 1.88% (DAF)
NO= 3455 PPM
(100% CONV)
- TOTAL NO
- FUEL NO
PREMIXED
RADIAL DIFFUSION
AXIAL DIFFUSION
NO (0% O2, DRY) PPM
% O2 (Stack)
1800
1600
1400
1200
1000
800
600
400
200
0
2
3
4
5
6
7
8
9

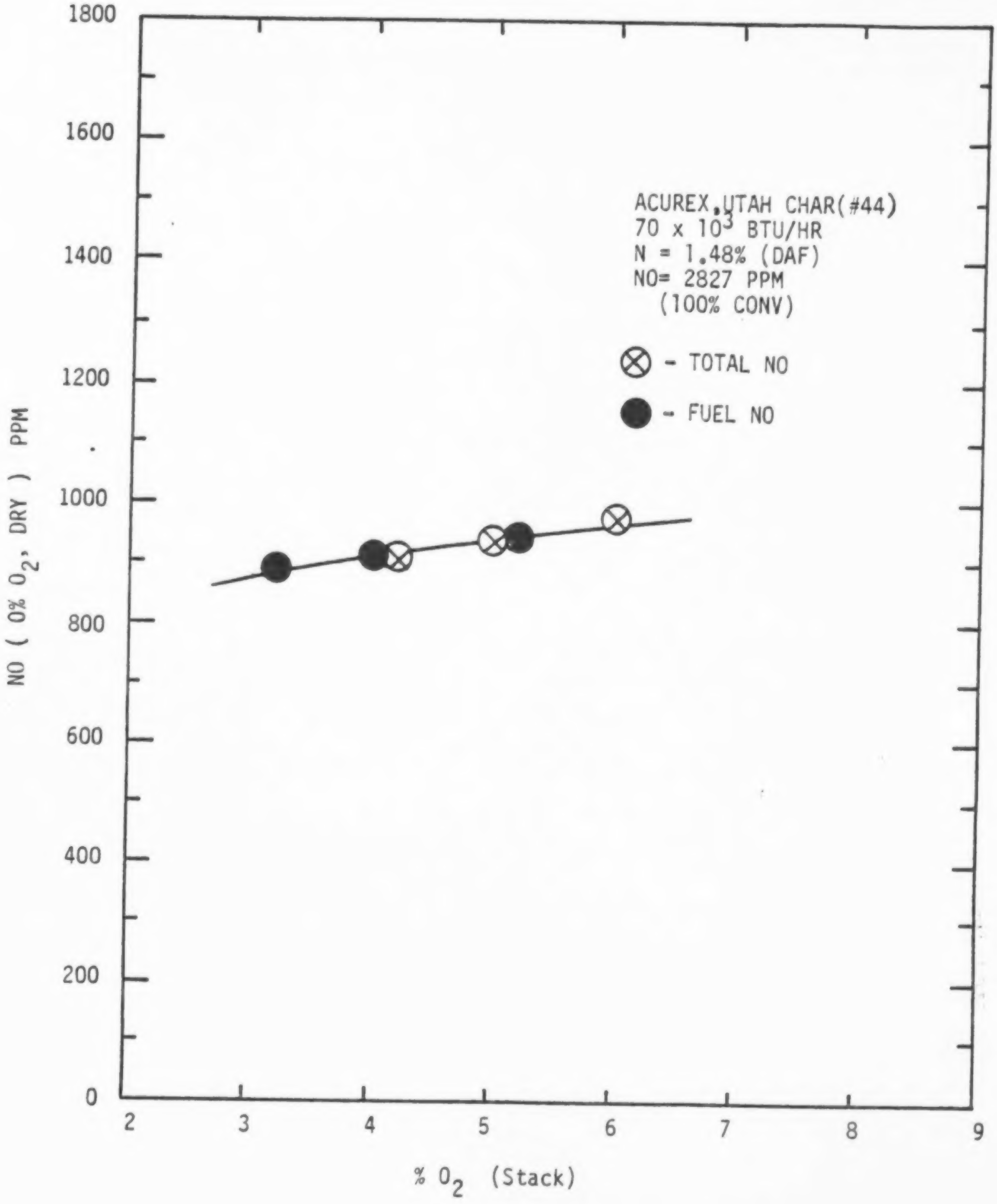

HARDIN,MONT.(#20)
70 x 10^3 BTU/HR
N = 1.11% (DAF)
NO= 2380 PPM
(100% CONV.)
▽ - TOTAL NO
▼ - FUEL NO
PREMIX
PREMIX
RADIAL
RADIAL
AXIAL
AXIAL
NO (0% O2, DRY) PPM
% O2 (Stack)
0
200
400
600
800
1000
1200
1400
1600
1800
2
3
4
5
6
7
8
9

GAULEY EAGLE, W.VA., (#24)
70 x 10³ BTU/HR
N = 1.87% (DAF)
NO= 3590 PPM
(100% CONV)
○ - TOTAL NO
● - FUEL NO
PREMIXED
RADIAL DIFFUSION
AXIAL DIFFUSION
(FLAME ATTACHED DISCONTINUOUSLY)
NO (0% O2, DRY) PPM
% O2 (Stack)
0
200
400
600
800
1000
1200
1400
1600
1800
2
3
4
5
6
7
8
9

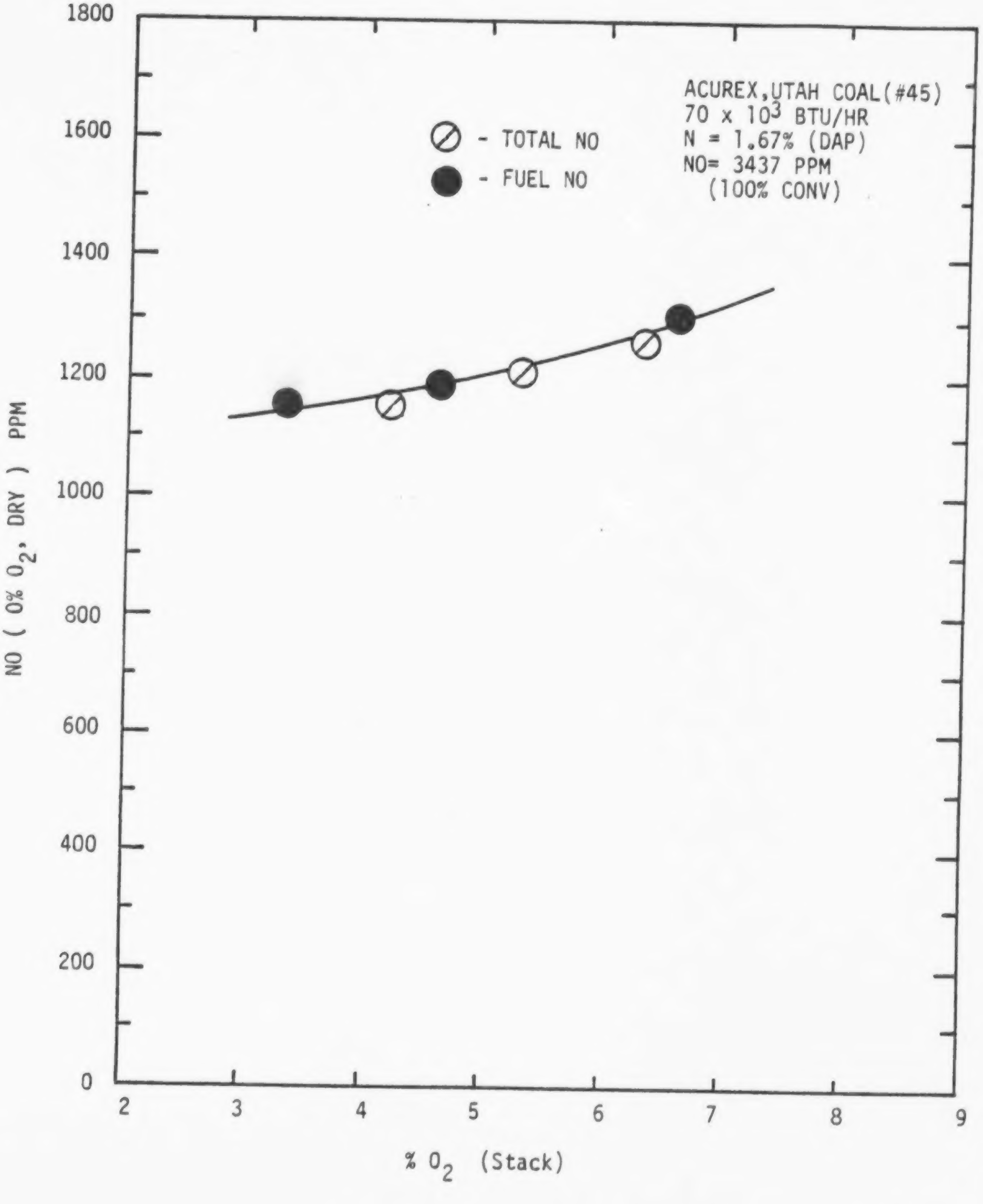

PENN. ANTHRACITE(#32)
70 x 10^3 BTU/HR
N = 0.84%(DAF)
NO= 1530
(100% CONV)
□ - TOTAL NO
■ - FUEL NO
AXIAL DIFFUSION
RADIAL DIFFUSION
AXIAL DIFFUSION
NO (0% O_2, DRY) PPM
1800
1600
1400
1200
1000
800
600
400
200
0
2
3
4
5
6
7
8
9
% O_2 (Stack)



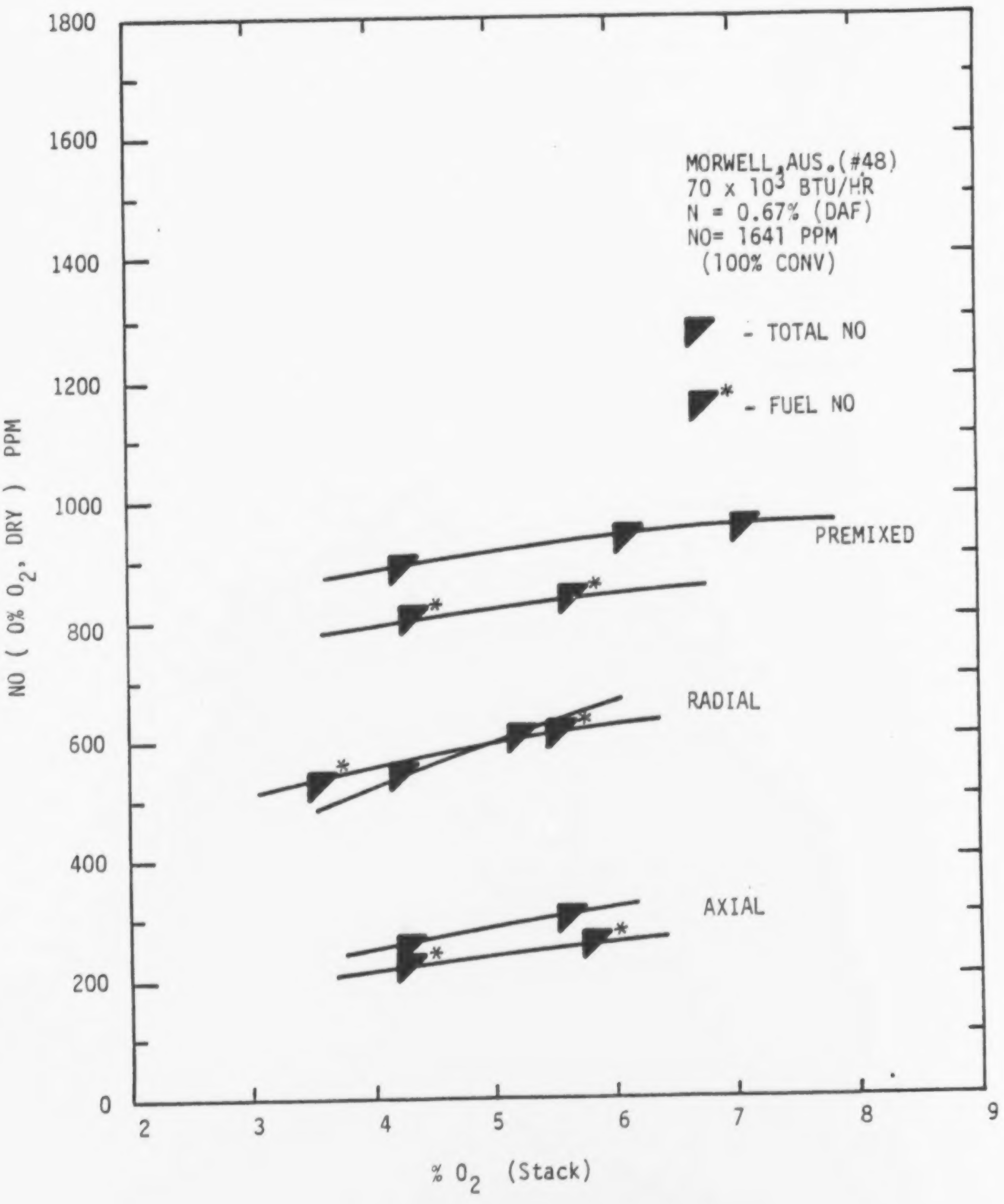
1800
1600
1400
1200
1000
800
600
400
200
0
2
3
4
5
6
7
8
9
NO (0% O2, DRY) PPM
% O2 (Stack)
TEXAS LIGNITE(#39)
70 x 10³ BTU/HR
N = 1.32% (DAF)
NO= 3070 PPM
(100% CONV)
- TOTAL NO
- FUEL NO
PREMIXED
AXIAL
RADIAL

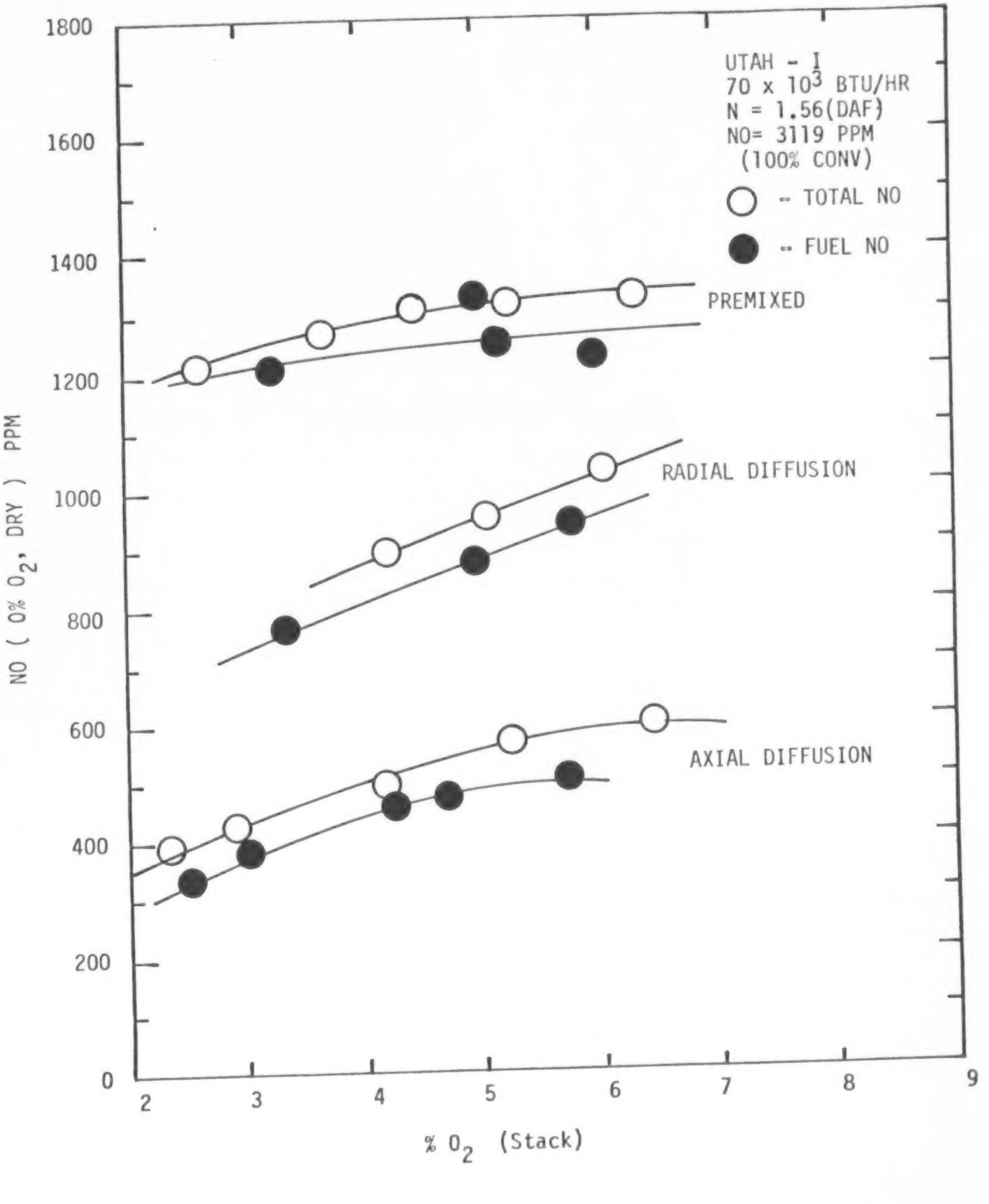


1800
1600
1400
1200
1000
800
600
400
200
0
2
3
4
5
6
7
8
9
NO (0% O_2, DRY) PPM
% O_2 (Stack)
ACUREX,UTAH CHAR(#44)
70 x 10^3 BTU/HR
N = 1.48% (DAF)
NO= 2827 PPM
(100% CONV)
⊗ - TOTAL NO
● - FUEL NO



ACUREX,UTAH COAL(#45)
70 x 10³ BTU/HR
N = 1.67% (DAP)
NO= 3437 PPM
(100% CONV)
Ø - TOTAL NO
● - FUEL NO
NO (0% O₂, DRY) PPM
0
200
400
600
800
1000
1200
1400
1600
1800
2
3
4
5
6
7
8
9
% O₂ (Stack)


MORWELL, AUS. (#48)
70 x 10³ BTU/HR
N = 0.67% (DAF)
NO= 1641 PPM
(100% CONV)
▼ - TOTAL NO
▼* - FUEL NO
PREMIXED
RADIAL
AXIAL
NO (0% O₂, DRY) PPM
% O₂ (Stack)
1800
1600
1400
1200
1000
800
600
400
200
0
2
3
4
5
6
7
8
9



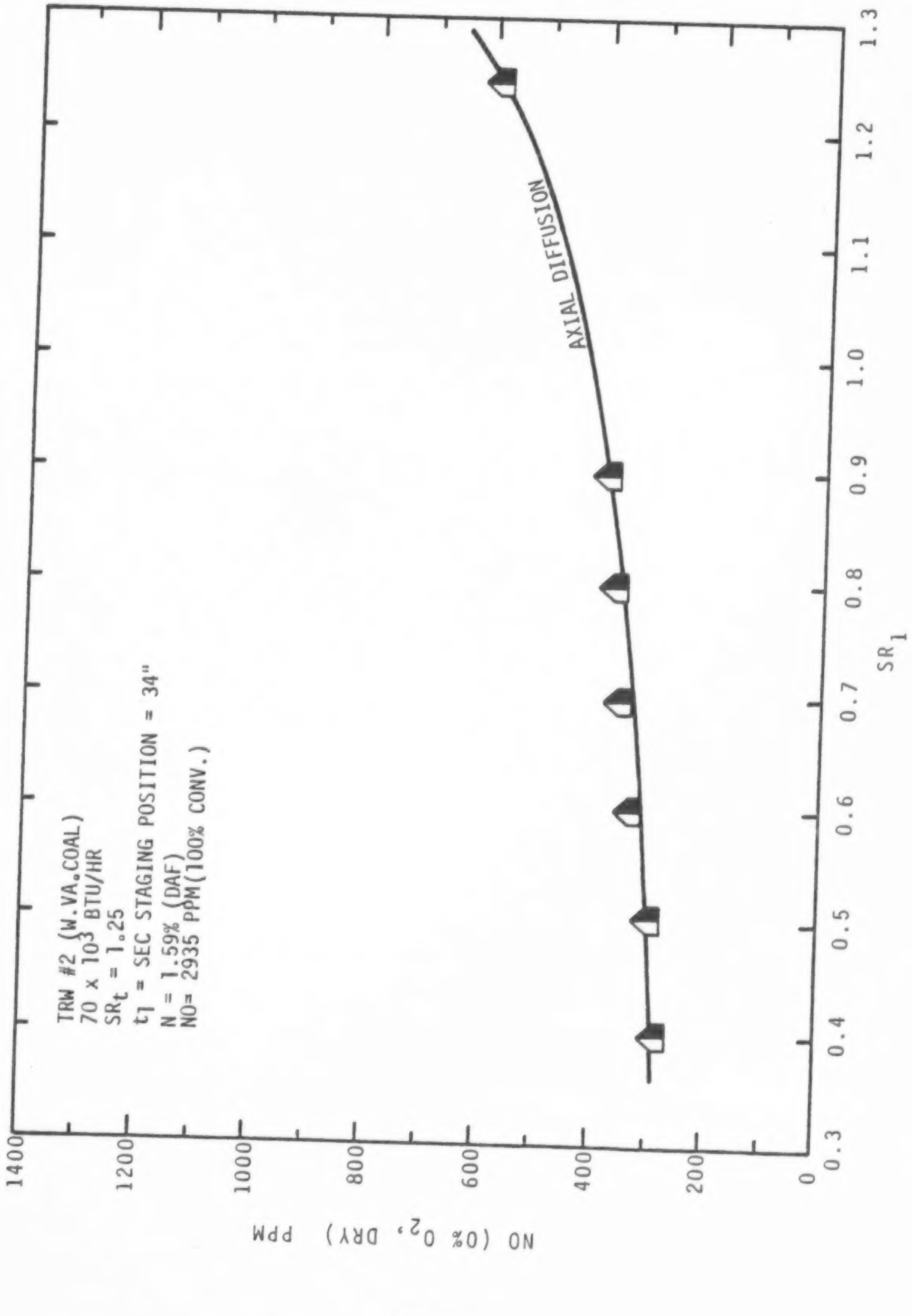
UTAH - I
70 x 10^3 BTU/HR
N = 1.56(DAF)
NO= 3119 PPM
(100% CONV)
○ - TOTAL NO
● - FUEL NO
PREMIXED
RADIAL DIFFUSION
AXIAL DIFFUSION
NO (0% O_2, DRY) PPM
% O_2 (Stack)
0
200
400
600
800
1000
1200
1400
1600
1800
2
3
4
5
6
7
8
9

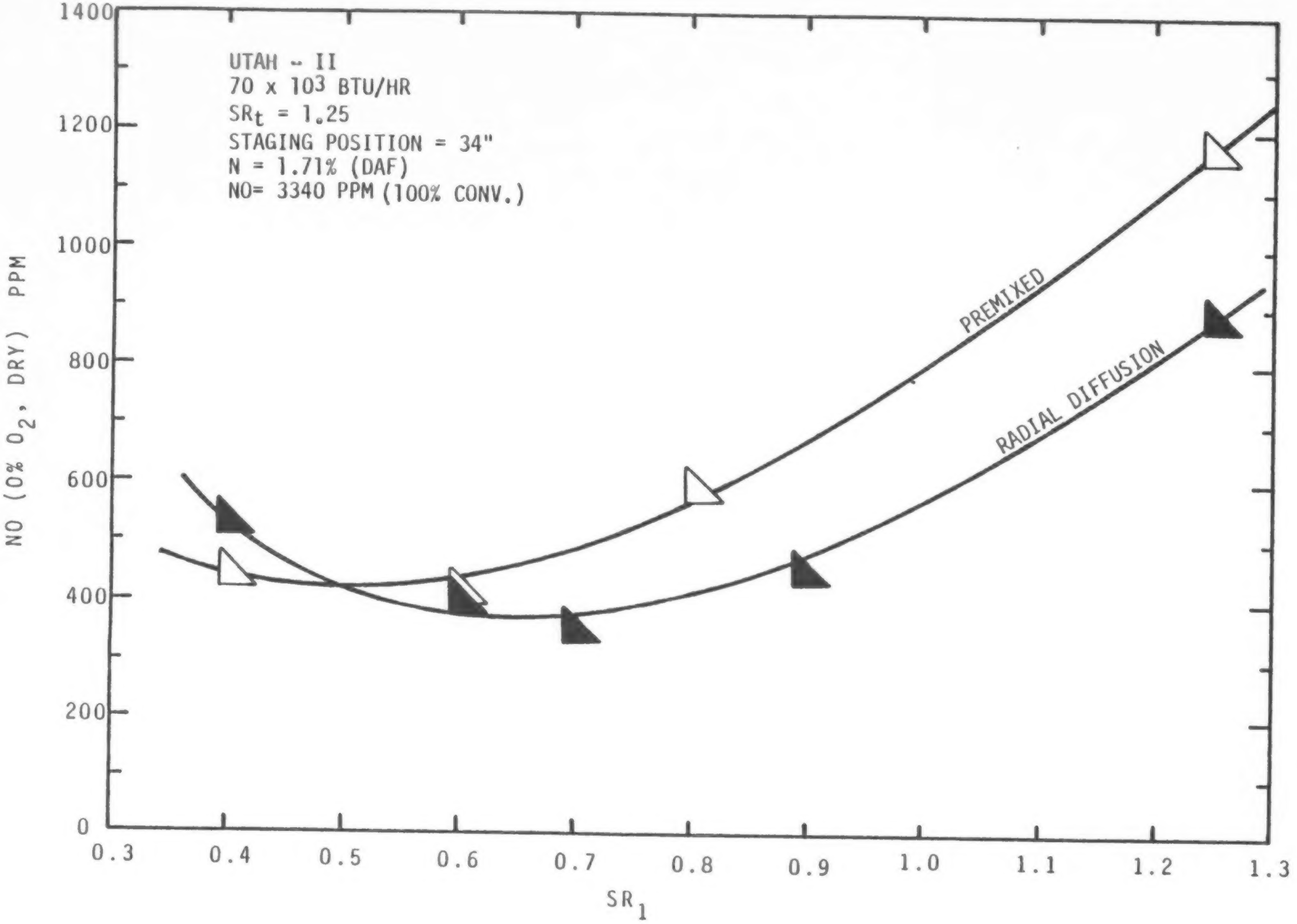
APPENDIX C

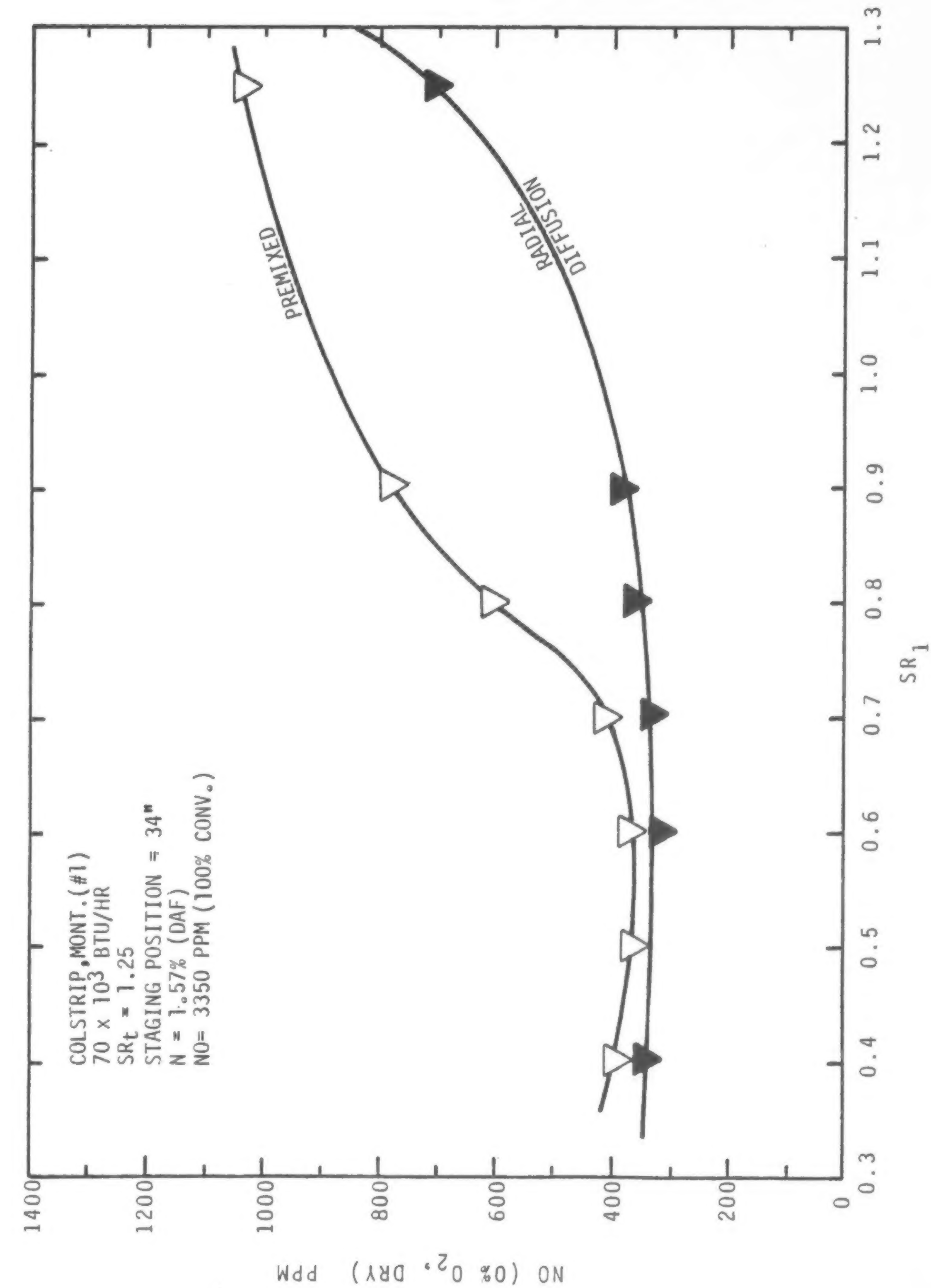
Summary of Bench-Scale Data

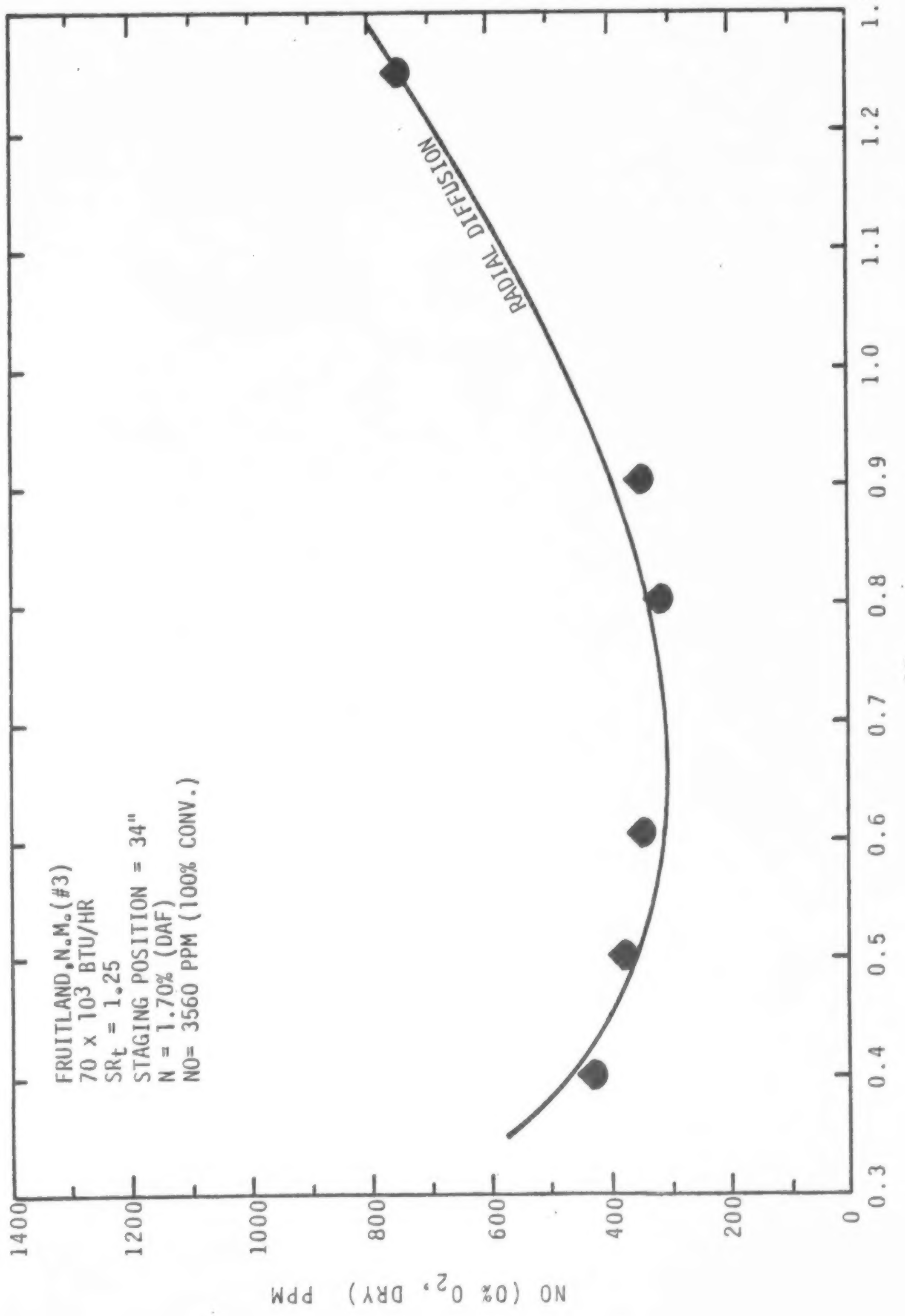
- NO_x Produced Under Simple Staged Conditions

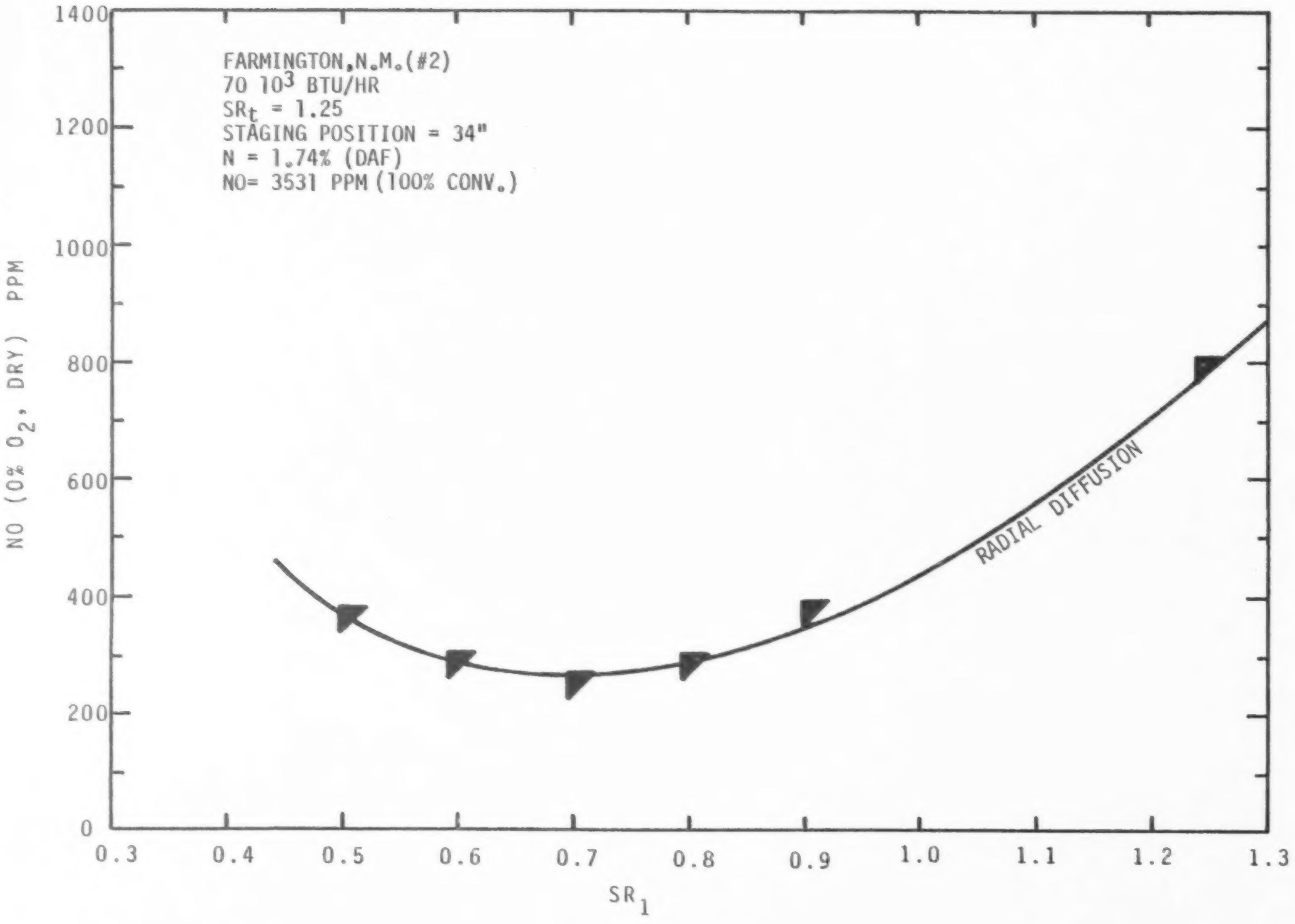
	Page
TRW No. 2 (W. V. Coal)	C-2
Utah II	C-3
Colstrip, Montana No. 1	C-4
Fruitland, N. M. No. 3	C-5
Farmington, N. M. No. 2	C-6
Scranton, N. D. No. 4	C-7
Beulah, N. D. No. 9	C-8
Savage, Montana No. 11	C-9
Cadiz, Ohio No. 13B	C-10
Elkay, W. V. No. 15	C-11
Upper Cliff, Alabama No. 17	C-12
Rosa, Alabama No. 18	C-13
Black Creek, Alabama No. 19	C-14
Hardin, Montana No. 20	C-15
Gauley Eagle, W. V. No. 24	C-16
Texas Lignite No. 39	C-17
Acurex, Utah Char No. 44	C-18
Acurex, Utah Coal No. 45	C-19
Composition of Ash for Coals	C-20

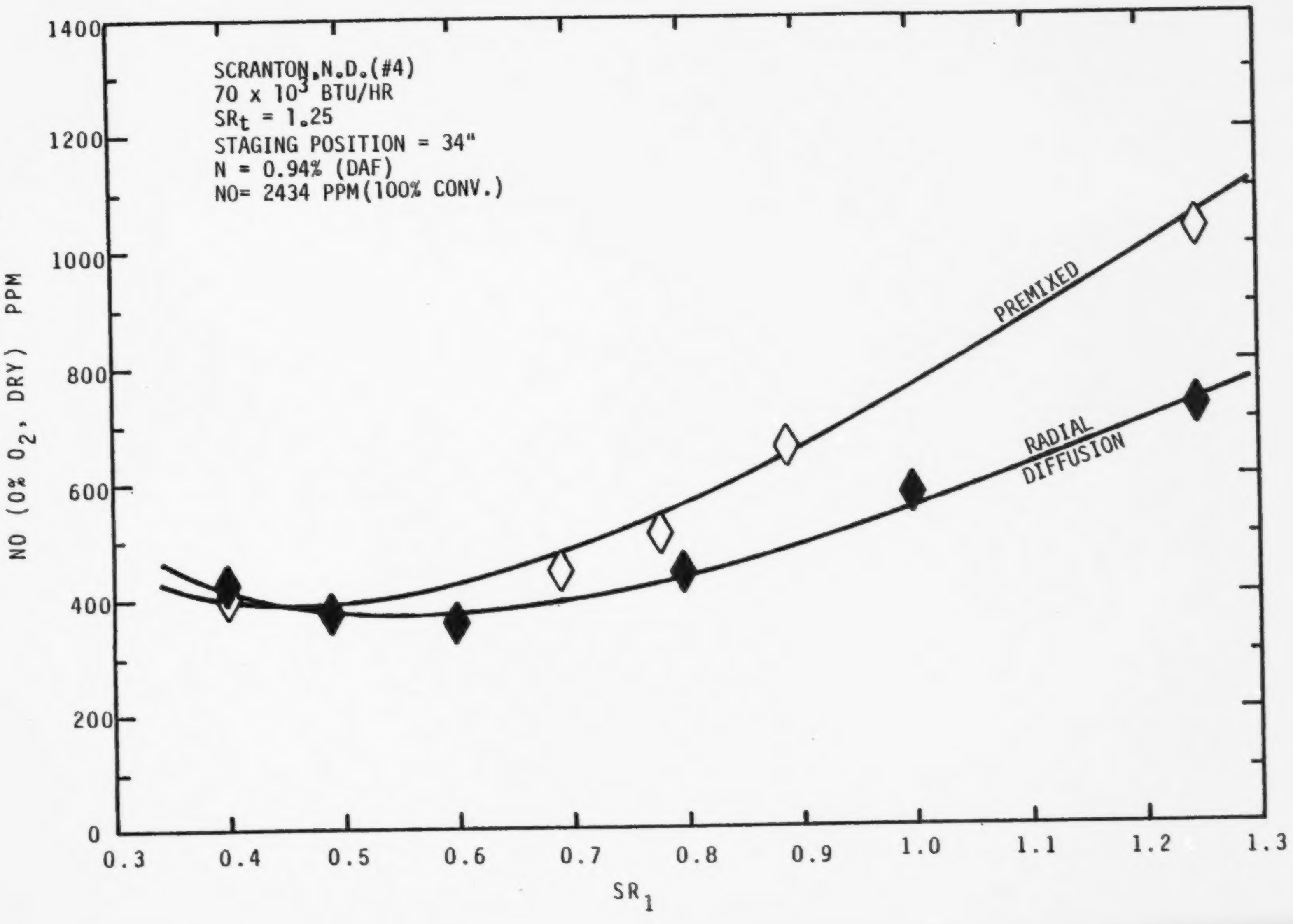

TRW #2 (W.VA.COAL)
70 x 10^3 BTU/HR
SR$_t$ = 1.25
t$_1$ = SEC STAGING POSITION = 34"
N = 1.59% (DAF)
NO= 2935 PPM(100% CONV.)
AXIAL DIFFUSION
NO (0% O$_2$, DRY) PPM
0
200
400
600
800
1000
1200
1400
SR$_1$
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3

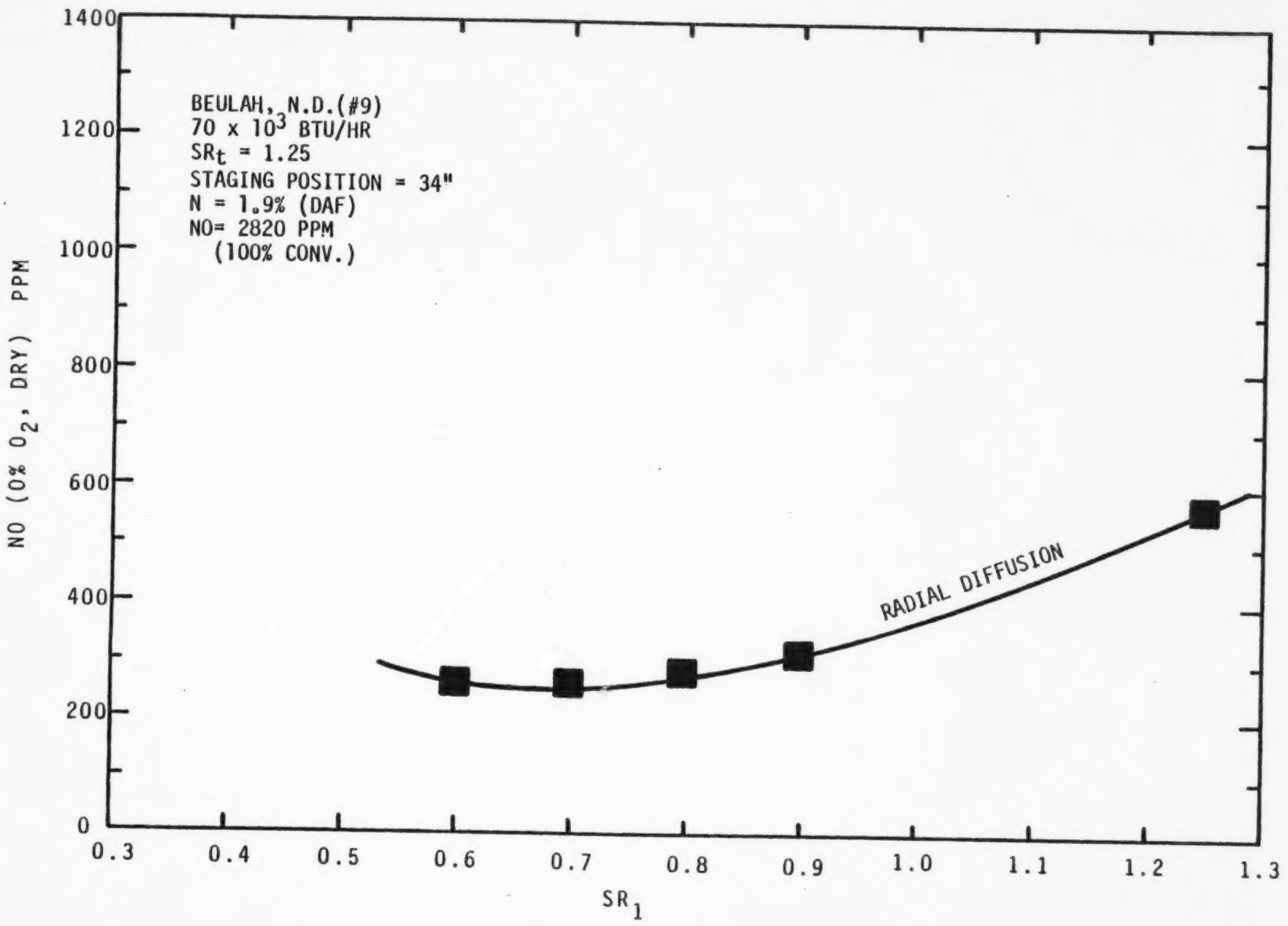

UTAH - II
70 x 10^3 BTU/HR
SR_t = 1.25
STAGING POSITION = 34"
N = 1.71% (DAF)
NO= 3340 PPM (100% CONV.)
PREMIXED
RADIAL DIFFUSION
NO (0% O_2, DRY) PPM
0
200
400
600
800
1000
1200
1400
SR_1
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3

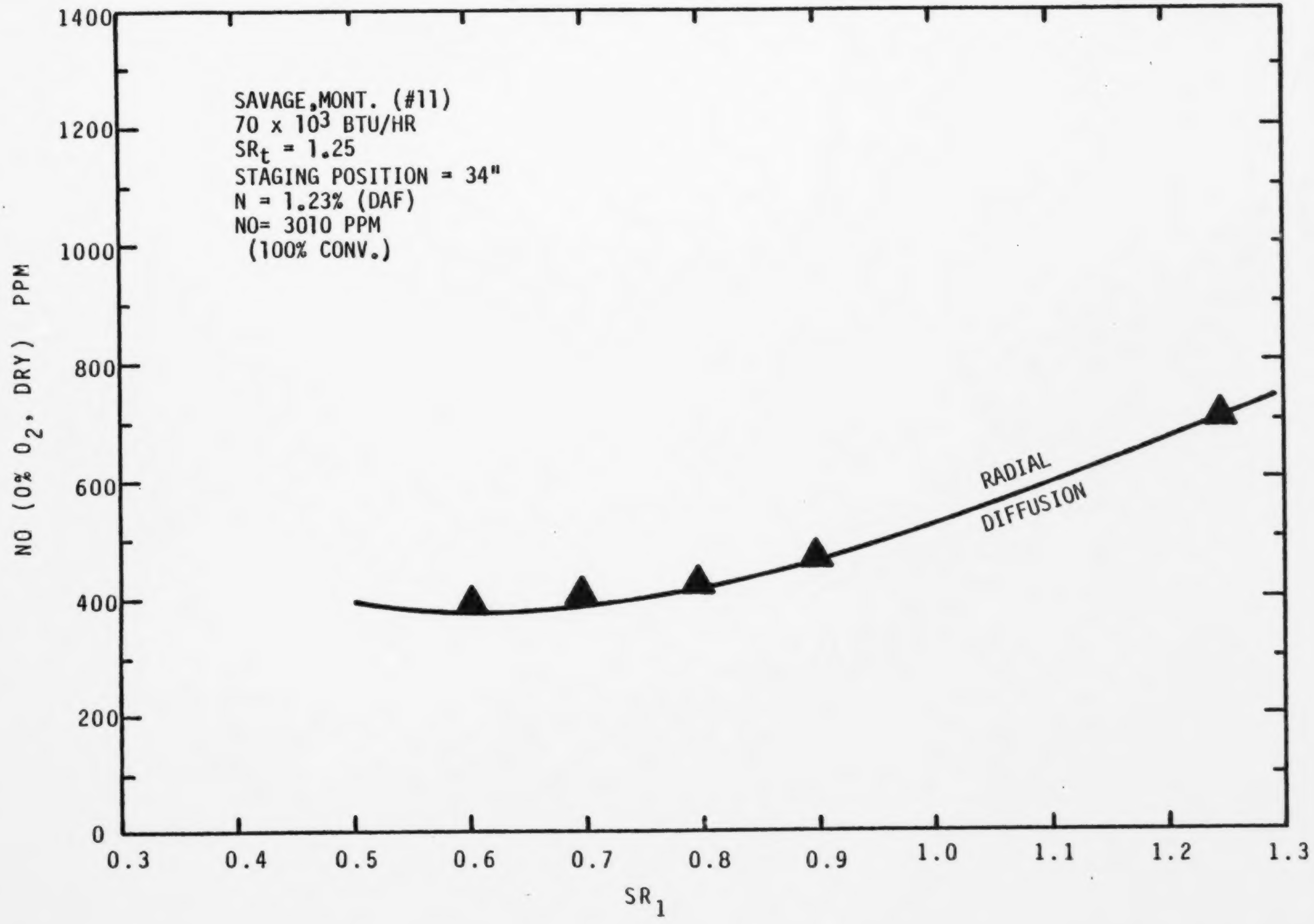

COLSTRIP, MONT. (#1)
70 x 10³ BTU/HR
SRt = 1.25
STAGING POSITION = 34"
N = 1.57% (DAF)
NO = 3350 PPM (100% CONV.)
PREMIXED
RADIAL DIFFUSION
NO (0% O2, DRY) PPM
0
200
400
600
800
1000
1200
1400
SR1
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3

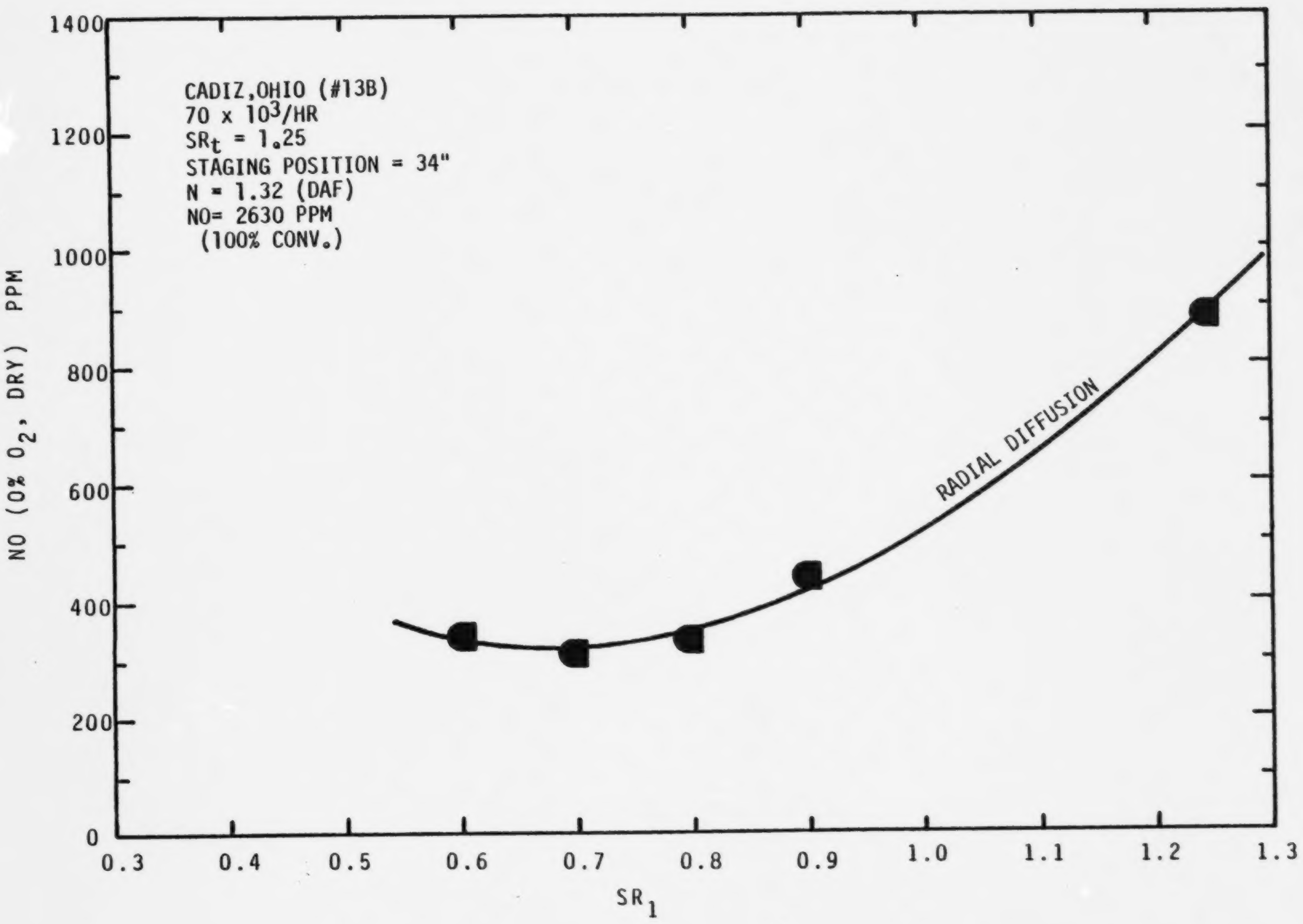

FRUITLAND, N.M. (#3)
70 x 10^3 BTU/HR
SR_t = 1.25
STAGING POSITION = 34"
N = 1.70% (DAF)
NO= 3560 PPM (100% CONV.)
RADIAL DIFFUSION
NO (0% O_2, DRY) PPM
SR_1
0
200
400
600
800
1000
1200
1400
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3

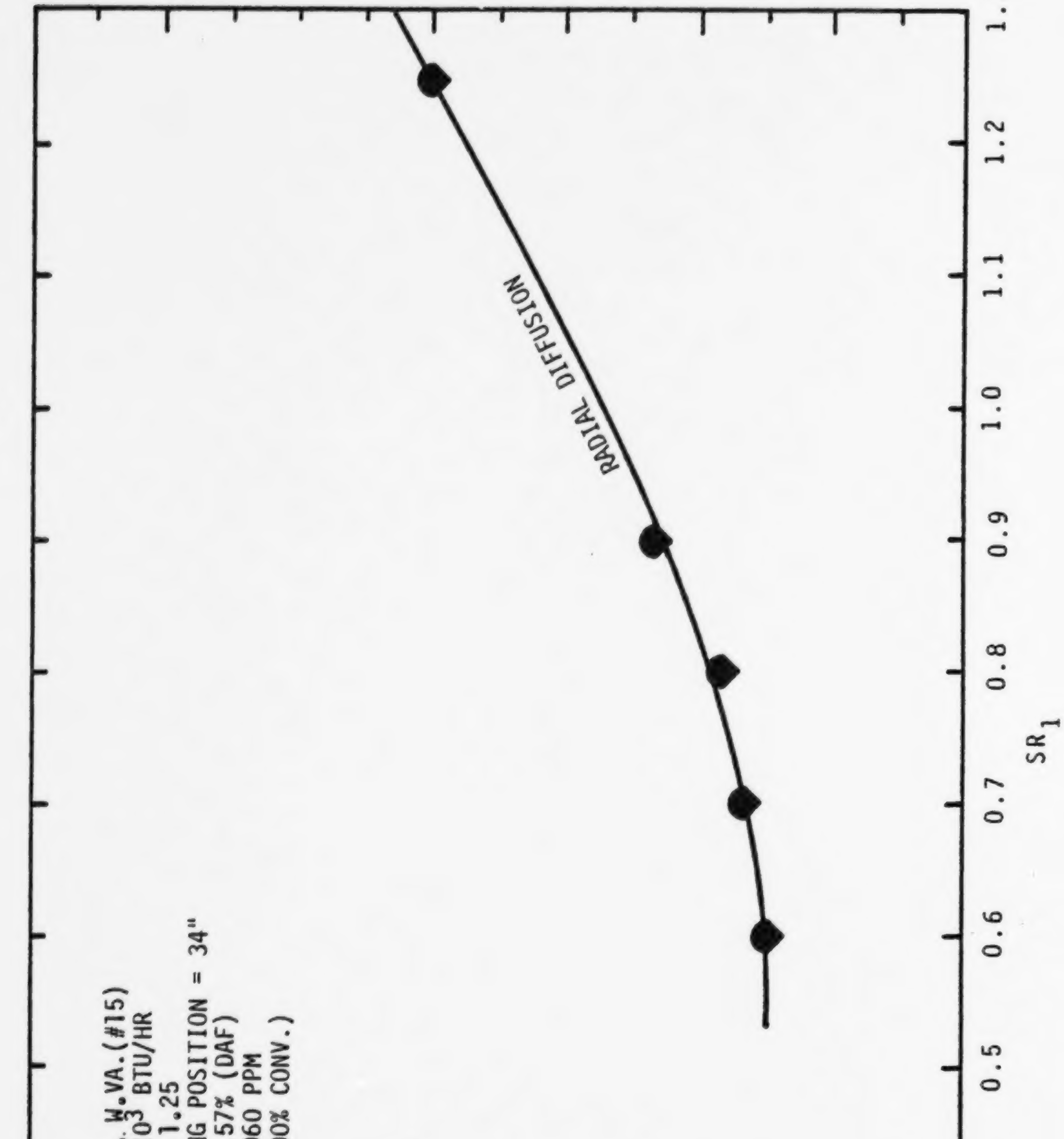

FARMINGTON,N.M.(#2)
70 10^3 BTU/HR
SR$_t$ = 1.25
STAGING POSITION = 34"
N = 1.74% (DAF)
NO= 3531 PPM (100% CONV.)
RADIAL DIFFUSION
NO (0% O$_2$, DRY) PPM
1400
1200
1000
800
600
400
200
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
SR$_1$

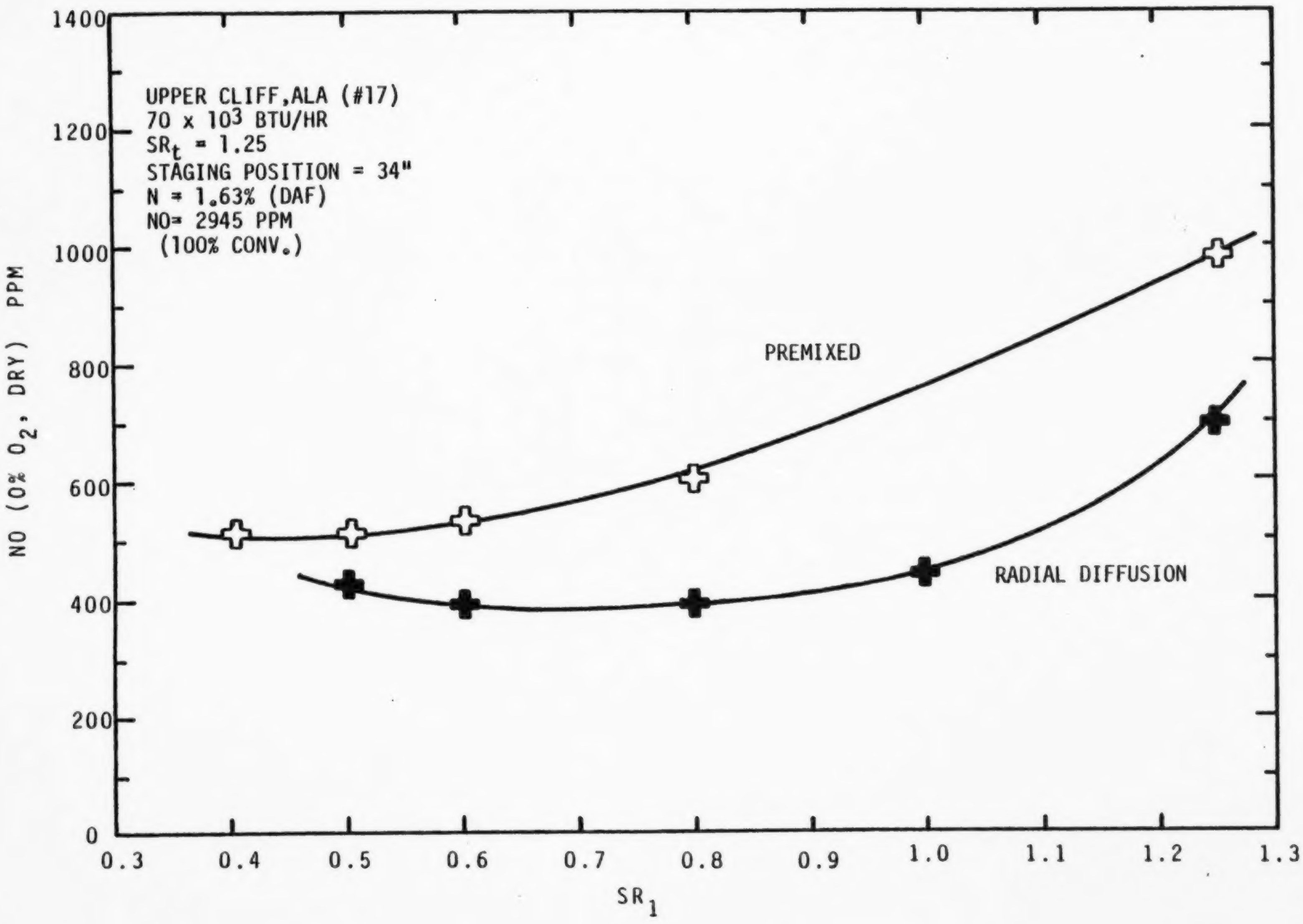

SCRANTON, N.D. (#4)
70 x 10^3 BTU/HR
SR_t = 1.25
STAGING POSITION = 34"
N = 0.94% (DAF)
NO= 2434 PPM(100% CONV.)
PREMIXED
RADIAL DIFFUSION
NO (0% O_2, DRY) PPM
0
200
400
600
800
1000
1200
1400
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
SR_1

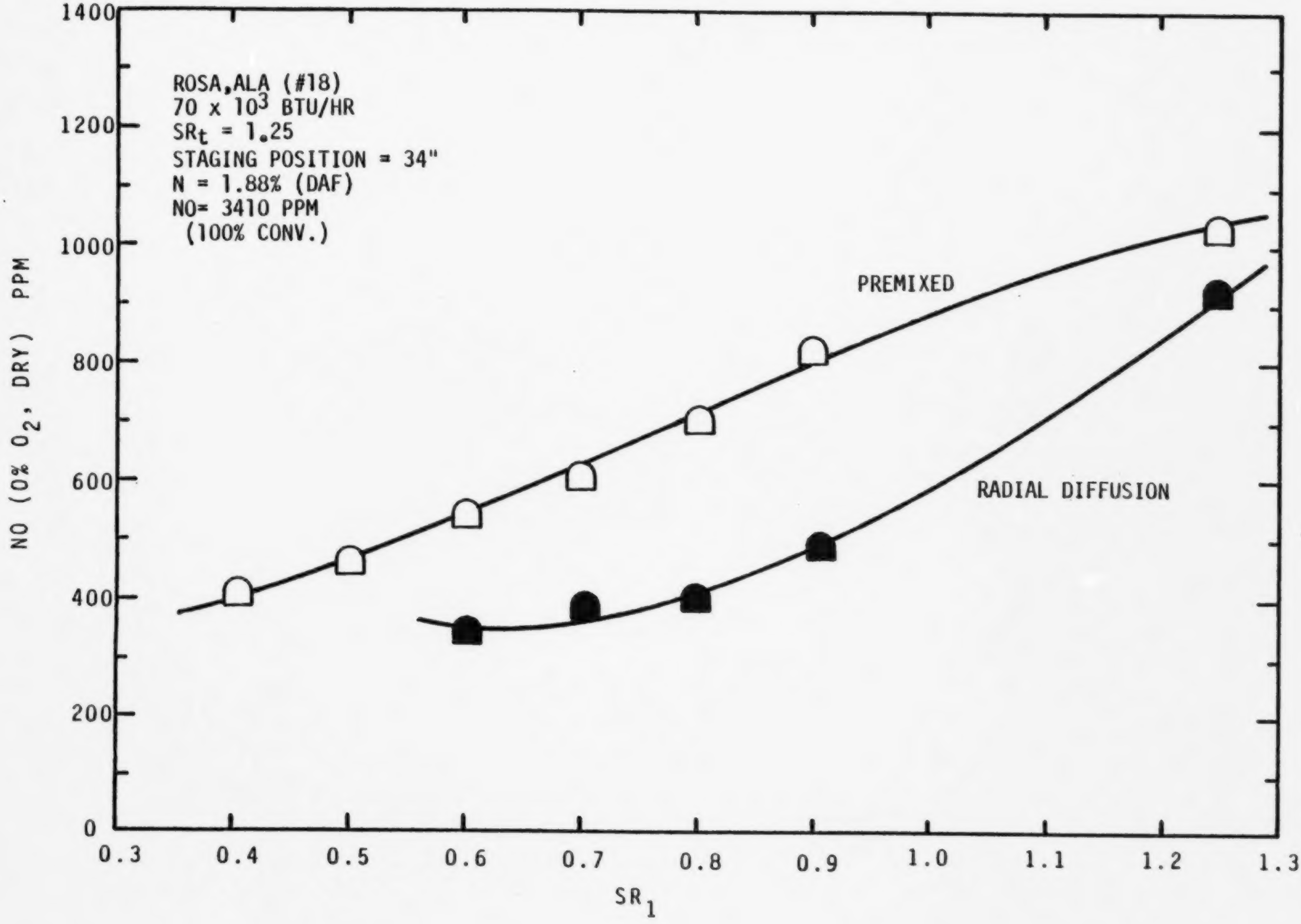

BEULAH, N.D.(#9)
70 x 10^3 BTU/HR
SR_t = 1.25
STAGING POSITION = 34"
N = 1.9% (DAF)
NO= 2820 PPM
(100% CONV.)
RADIAL DIFFUSION
NO (0% O_2, DRY) PPM
1400
1200
1000
800
600
400
200
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
SR_1

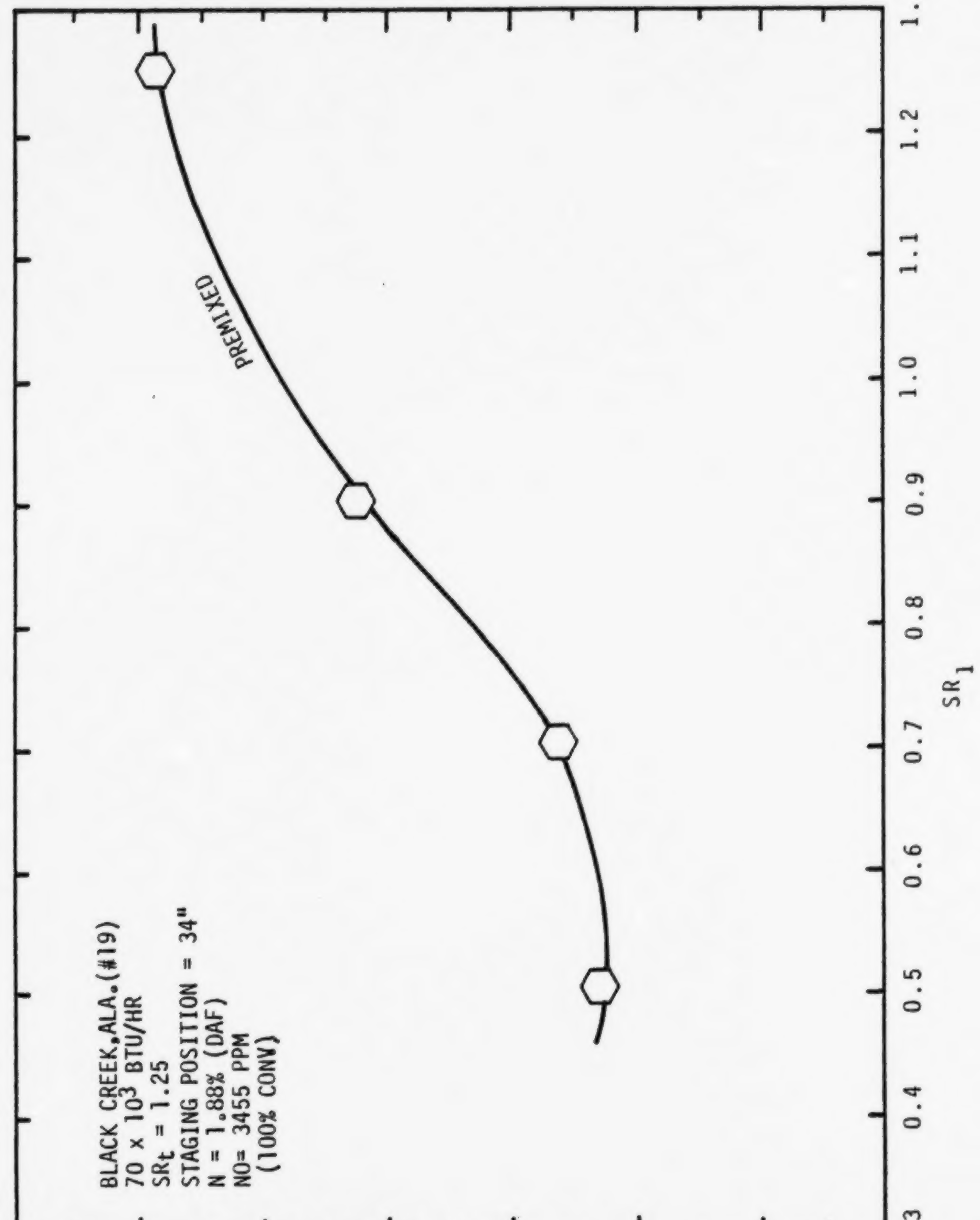

SAVAGE, MONT. (#11)
70 x 10^3 BTU/HR
SR_t = 1.25
STAGING POSITION = 34"
N = 1.23% (DAF)
NO= 3010 PPM
(100% CONV.)
RADIAL
DIFFUSION
NO (0% O_2, DRY) PPM
1400
1200
1000
800
600
400
200
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
SR_1

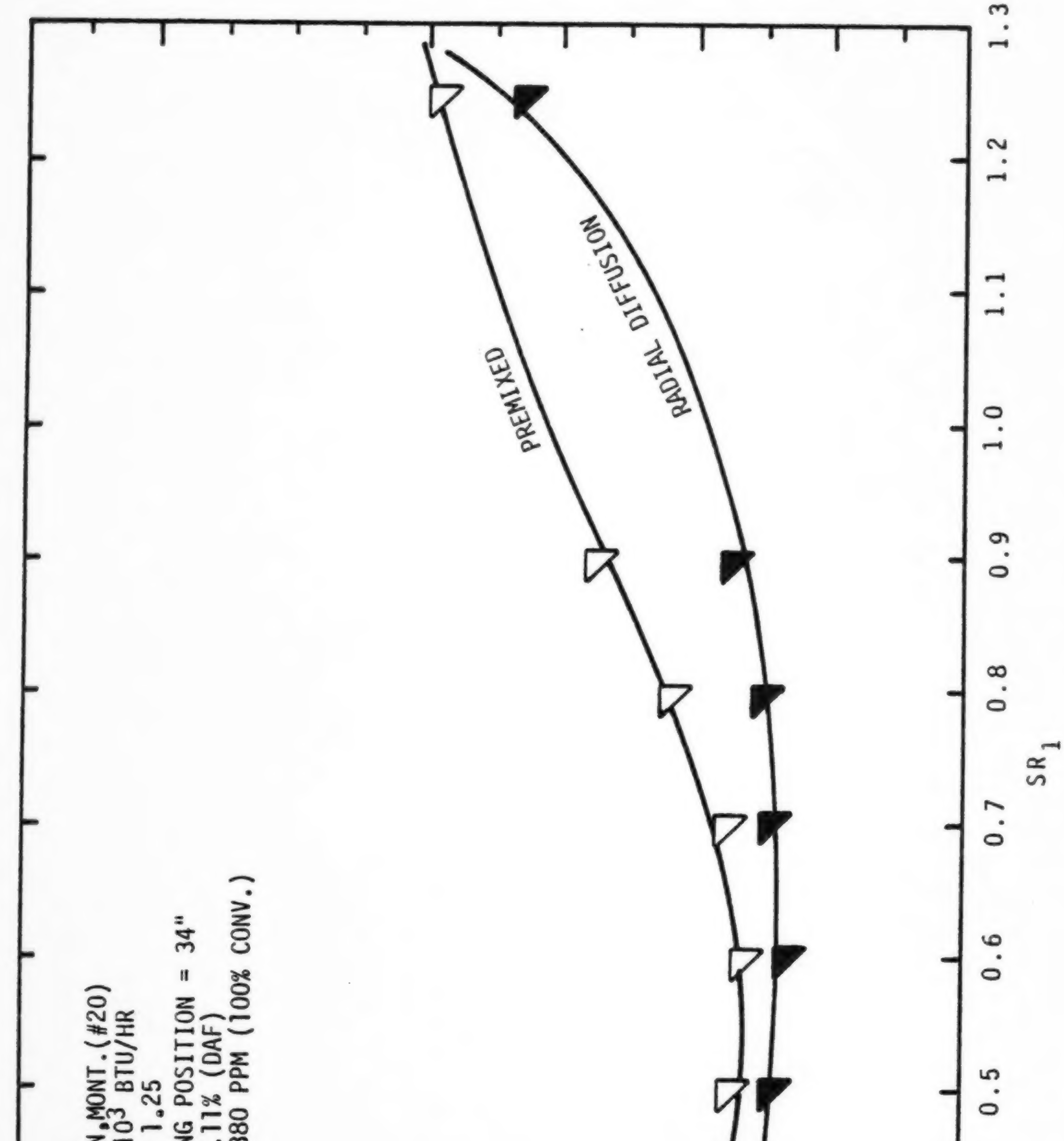

CADIZ,OHIO (#13B)
70 x 10^3/HR
SR$_t$ = 1.25
STAGING POSITION = 34"
N = 1.32 (DAF)
NO= 2630 PPM
(100% CONV.)
RADIAL DIFFUSION
NO (0% O$_2$, DRY) PPM
1400
1200
1000
800
600
400
200
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
SR$_1$

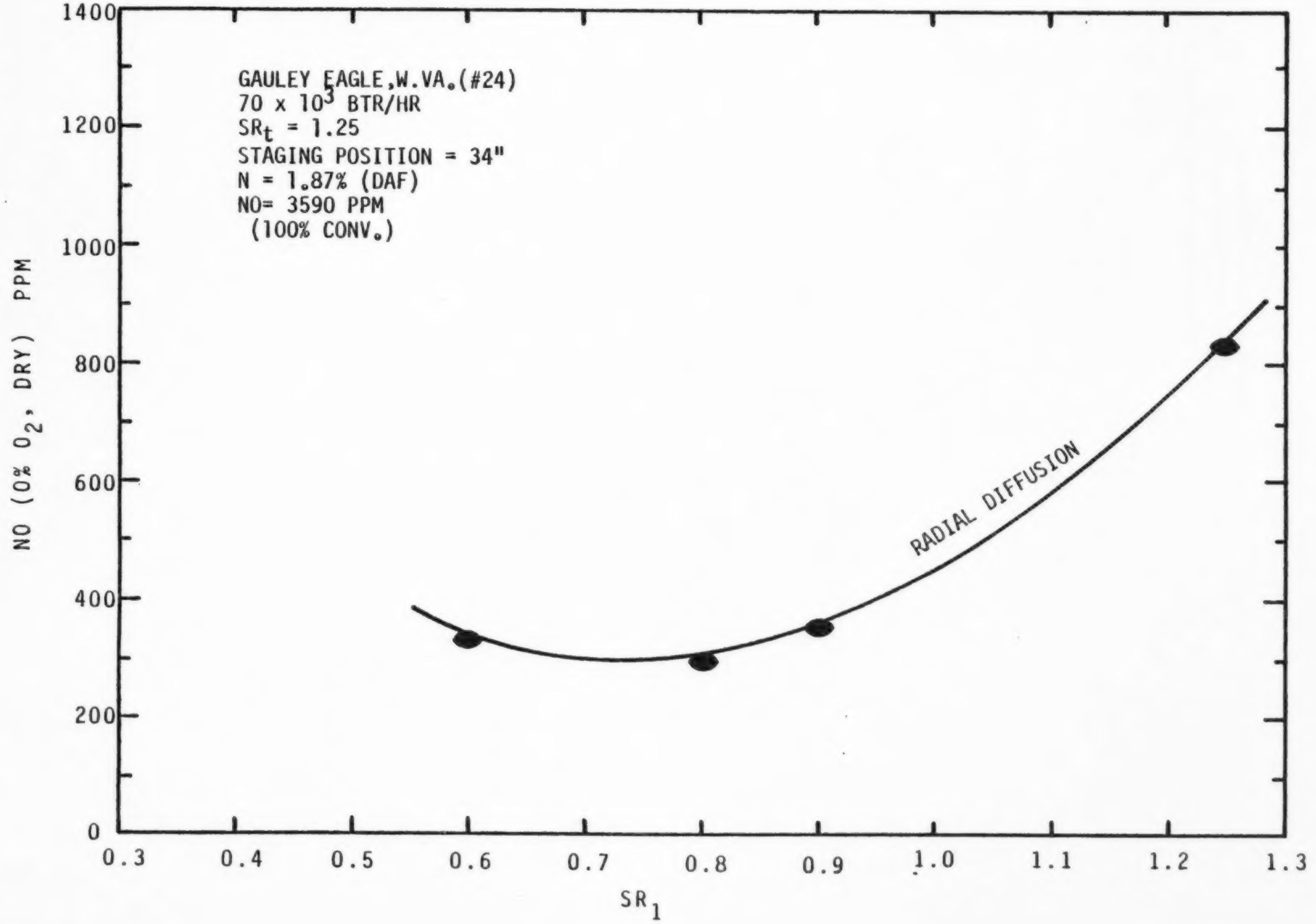

ELKAY, W.VA. (#15)
70 x 10^3 BTU/HR
SR$_t$ = 1.25
STAGING POSITION = 34"
N = 1.57% (DAF)
NO= 2960 PPM
(100% CONV.)
RADIAL DIFFUSION
NO (0% O$_2$, DRY) PPM
0
200
400
600
800
1000
1200
1400
SR$_1$
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3

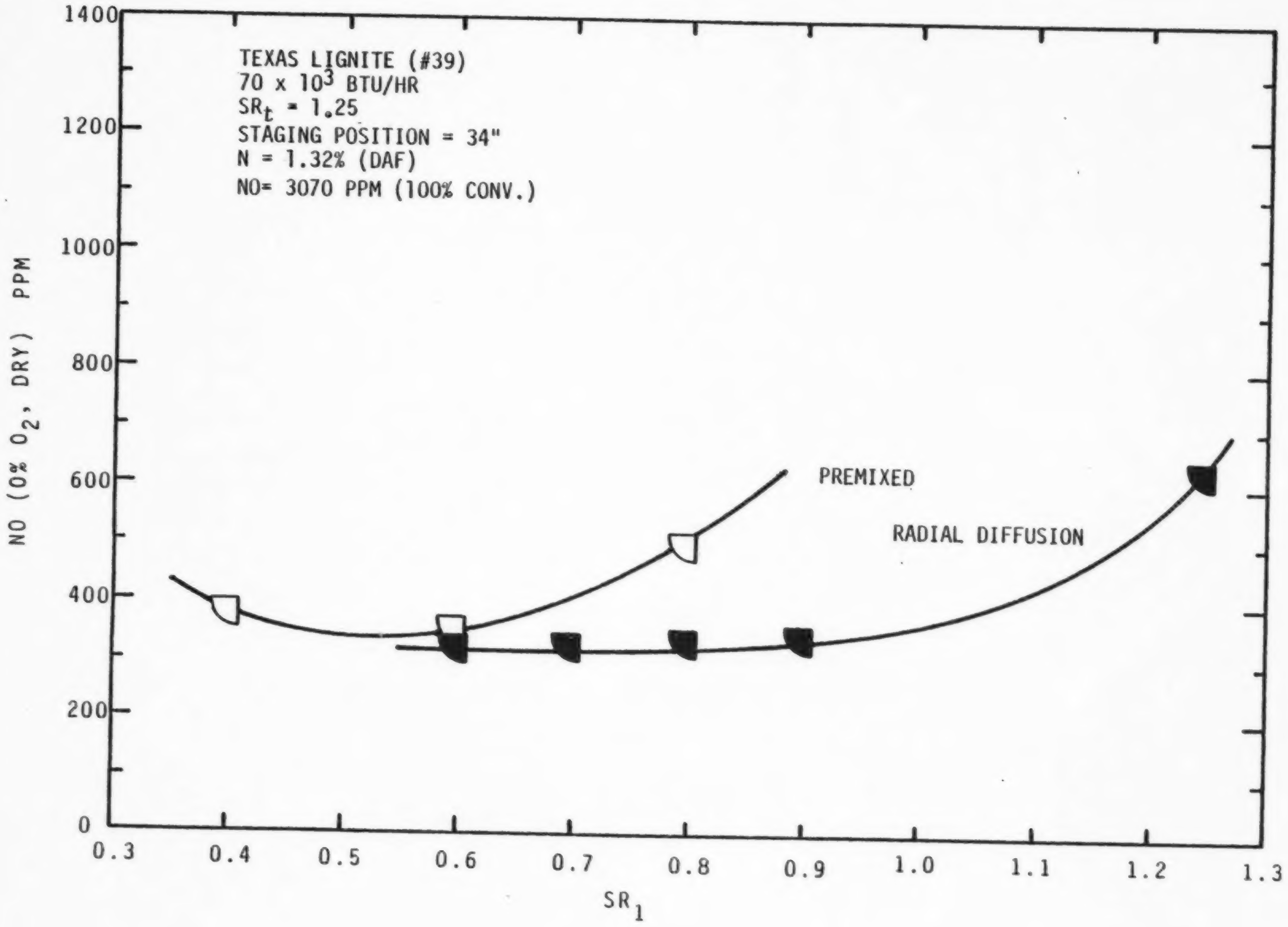

UPPER CLIFF,ALA (#17)
70 x 10^3 BTU/HR
SR_t = 1.25
STAGING POSITION = 34"
N = 1.63% (DAF)
NO= 2945 PPM
(100% CONV.)
PREMIXED
RADIAL DIFFUSION
NO (0% O_2, DRY) PPM
0
200
400
600
800
1000
1200
1400
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
SR_1

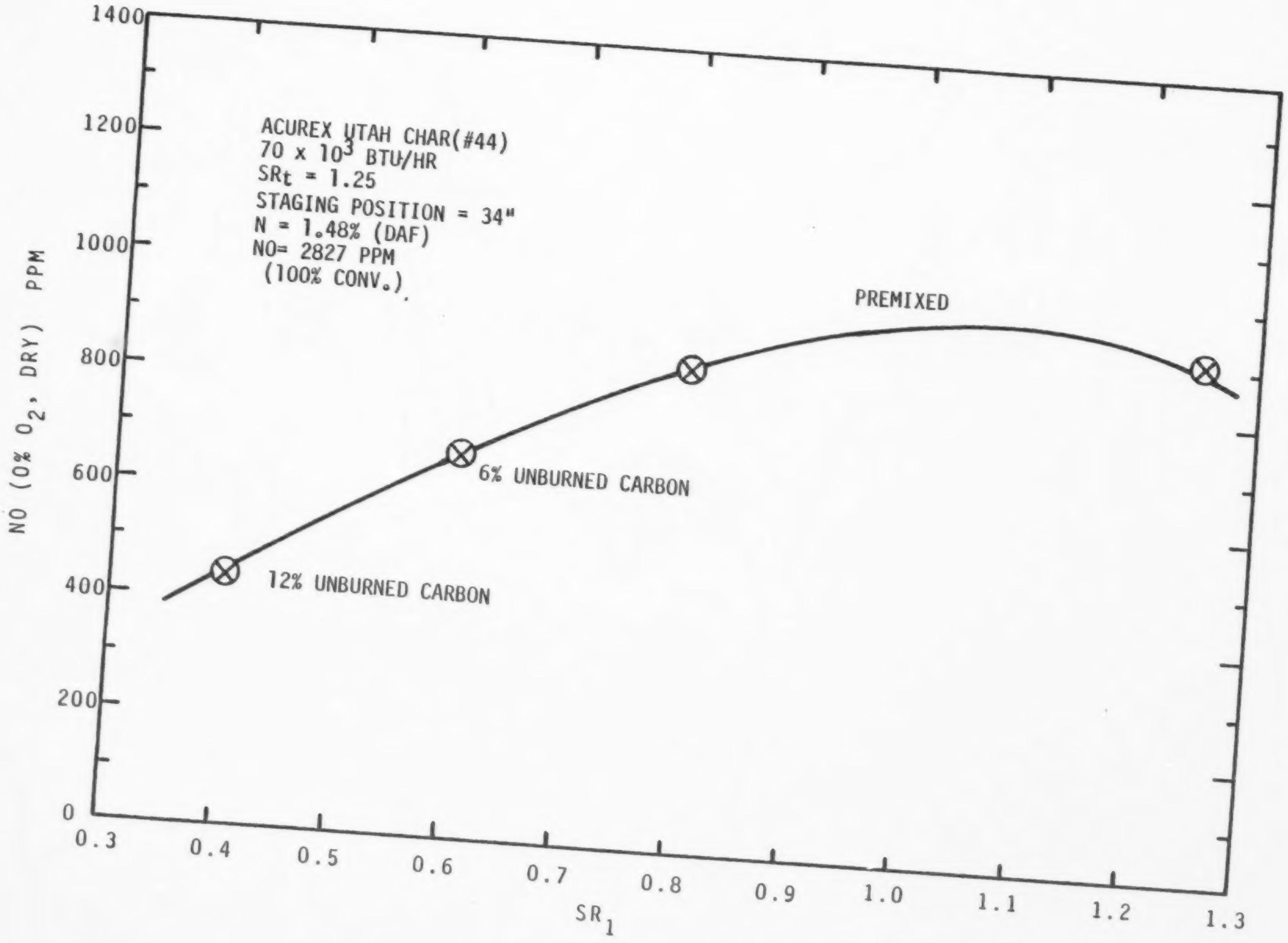

ROSA, ALA (#18)
70 x 10^3 BTU/HR
SR_t = 1.25
STAGING POSITION = 34"
N = 1.88% (DAF)
NO= 3410 PPM
(100% CONV.)
PREMIXED
RADIAL DIFFUSION
NO (0% O_2, DRY) PPM
0
200
400
600
800
1000
1200
1400
SR_1
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3

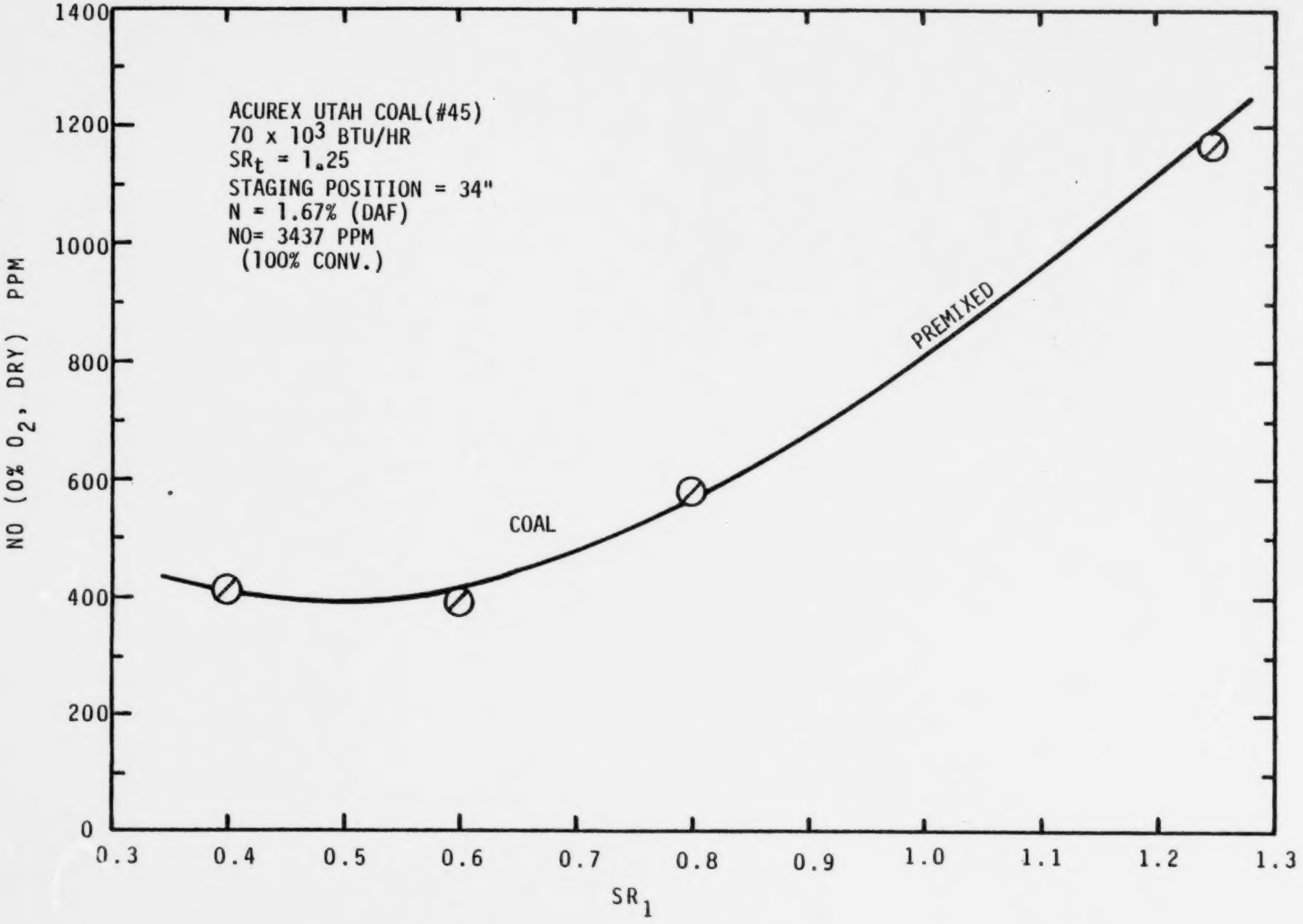

BLACK CREEK, ALA. (#19)
70 x 10³ BTU/HR
SRt = 1.25
STAGING POSITION = 34"
N = 1.88% (DAF)
NO= 3455 PPM
(100% CONV)
PREMIXED
NO (0% O2, DRY) PPM
1400
1200
1000
800
600
400
200
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
SR1


HARDIN, MONT. (#20)
70 x 10^3 BTU/HR
SR$_t$ = 1.25
STAGING POSITION = 34"
N = 1.11% (DAF)
NO= 2380 PPM (100% CONV.)
PREMIXED
RADIAL DIFFUSION
NO (0% O$_2$, DRY) PPM
0
200
400
600
800
1000
1200
1400
SR$_1$
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3


GAULEY EAGLE,W.VA.(#24)
70 x 10^3 BTR/HR
SR_t = 1.25
STAGING POSITION = 34"
N = 1.87% (DAF)
NO= 3590 PPM
(100% CONV.)
RADIAL DIFFUSION
NO (0% O_2, DRY) PPM
0
200
400
600
800
1000
1200
1400
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
SR_1


TEXAS LIGNITE (#39)
70 x 10^3 BTU/HR
SR_t = 1.25
STAGING POSITION = 34"
N = 1.32% (DAF)
NO= 3070 PPM (100% CONV.)
PREMIXED
RADIAL DIFFUSION
NO (0% O_2, DRY) PPM
0
200
400
600
800
1000
1200
1400
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
SR_1

ACUREX UTAH CHAR(#44)
70 x 10³ BTU/HR
SRt = 1.25
STAGING POSITION = 34"
N = 1.48% (DAF)
NO= 2827 PPM
(100% CONV.)
PREMIXED
6% UNBURNED CARBON
12% UNBURNED CARBON
NO (0% O₂, DRY) PPM
0
200
400
600
800
1000
1200
1400
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
SR₁


ACUREX UTAH COAL(#45)
70 x 10^3 BTU/HR
SR$_t$ = 1.25
STAGING POSITION = 34"
N = 1.67% (DAF)
NO= 3437 PPM
(100% CONV.)
PREMIXED
COAL
NO (0% O$_2$, DRY) PPM
1400
1200
1000
800
600
400
200
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
SR$_1$

APPENDIX C

COMPOSITION OF ASH FOR COALS AVAILABLE FOR TESTING

No.	Coal	ASH	Wt. % of ASH (dry)								
		(%,dry)	Na_2O	K_2O	CaO	MgO	Al_2O_3	S_1O_2	Fe_2O_3	TiO_2	SO_3
-	Utah I	7.89	0.66	0.46	4.23	0.67	15.67	56.69	3.04	0.93	18.23
-	Utah II	9.54	0.61	0.94	4.92	0.87	13.14	59.00	3.58	0.67	16.46
-	TRW 1	17.75	0.77	2.03	1.58	0.62	17.39	53.57	6.10	0.17	18.04
-	TRW 2 W.Va.	13.04	0.50	1.74	2.57	0.67	25.42	48.43	3.60	0.62	16.46
-	TRW 3 W.Ky.	8.82	0.39	1.77	1.45	0.58	22.17	42.18	7.35	0.48	23.98
1	Colstrip,Mont	12.17	0.87	0.20	14.53	5.28	18.33	45.50	1.15	0.80	13.34
2	Farmington,N.M	19.47	1.78	0.95	4.71	1.08	29.36	47.79	4.38	0.44	9.51
3	Fruitland,N.M	23.29	2.26	0.82	5.44	1.06	33.86	42.42	4.84	0.41	8.89
4	Scranton,N.D.	10.12	3.52	0.12	20.93	7.88	8.56	14.85	6.13	0.37	37.64
5	Kemmerer,Wy	3.47									
6	Beulah, N.D.	10.64	1.01	0.24	13.11	3.78	11.35	34.95	6.65	0.45	28.62
7	Colorado Coal	7.67	0.53	0.62	2.09	0.36	12.25	32.14	14.48	0.70	37.22
8	Hardin,Mont.	14.57									
9	Beulah,N.D.	7.60	11.34	0.21	21.51	6.49	9.80	29.36	5.69	0.48	15.28
10	Velva,N.D.	11.70	1.48	0.69	22.95	5.52	9.10	42.30	7.87	0.38	10.14
11	Montana Savage	7.25	0.68	0.15	33.82	15.38	10.06	14.75	5.75	0.43	19.11
12	Paonia, Col.	6.69	0.91	0.38	10.09	1.46	16.97	50.76	4.27	0.64	14.69
13A	Cadiz,DH-13A OH	13.59									
13B	Cadiz,Ohio	18.86	0.17	0.20	0.18	0.03	3.24	3.68	22.12	0.14	73.00

APPENDIX C

COMPOSITION OF ASH FOR COALS AVAILABLE FOR TESTING

No.	Coal	ASH (%,dry)	Wt. % of ASH (dry) Na_2O	K_2O	CaO	MgO	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	SO_3
14	Buffalo Mark, W.Va.	15.75	0.73	2.22	2.89	1.03	17.23	47.59	8.52	0.36	19.43
15	Elkay, W. Va.	11.69	0.63	2.67	3.92	1.11	19.71	43.02	11.54	0.04	17.48
16	Sewanee, Ala.	8.96	0.41	2.27	2.29	0.90	16.65	50.93	8.30	0.33	18.37
17	Upper Cliff, Ala	9.78	0.62	1.64	1.63	0.38	16.60	39.71	14.14	0.44	24.58
18	Rosa, Ala.	7.38	0.78	1.87	2.51	0.97	10.86	41.94	11.11	0.46	30.09
19	Black Creek,Ala	4.56	0.68	1.37	2.60	0.69	18.14	42.09	8.17	0.58	26.09
20	Hardin, Mont.	10.84	5.03	0.20	23.09	3.22	14.23	37.86	2.39	0.59	13.57
21	Lema, Colorado	23.51	0.40	1.30	4.52	1.18	28.16	54.02	2.32	0.43	7.87
22	Way Lawn, Ky.	4.54	0.60	1.90	4.17	1.17	14.58	41.01	9.47	0.61	26.80
23	Upshur,L-Kittanning	16.90	0.26	1.73	1.68	0.62	33.83	36.44	9.24	0.44	16.09
24	Gauley Eagle,Kittanning	27.94	0.50	3.87	5.66	1.49	41.98	34.82	5.44	0.00	7.08
25	Meigs-Clarion 4A OH-25	34.17	0.68	1.78	2.40	0.96	28.46	26.89	12.00	0.35	26.54
26	Ridge 5,L-Kittanning	36.24	0.46	4.67	1.46	1.41	69.65	9.96	5.56	0.00	8.23
27	Martinke,L-Kittanning 5 Block-27	41.72	0.91	3.85	2.36	1.47	71.70	0.00	14.60	0.00	15.13
28	Coalburg, Central Appalachian	26.97	0.46	5.39	1.60	1.37	60.76	23.18	3.64	0.00	5.25
29	Beech Bottom Pittsburg 8	39.69	0.74	2.80	1.96	1.28	44.21	20.72	13.67	0.00	14.99

APPENDIX C

COMPOSITION OF ASH FOR COALS AVAILABLE FOR TESTING

		ASH	Wt. % of ASH (dry)								
No.	Coal	(%,dry)	Na_2O	K_2O	CaO	MgO	Al_2O_3	S_1O_2	Fe_2O_3	TiO_2	SO_3
30	Freeport,Lower Freeport-30	40.30	0.57	5.03	1.45	1.78	61.16	17.23	8.07	0.00	5.93
31	Muskingum, Meigs Creek 9-31	24.64	0.52	0.97	1.73	0.72	13.98	29.96	11.53	0.49	40.46
32	Anthracite, Hazelton,PA	8.62	0.10	1.43	2.69	0.38	22.41	52.65	7.20	2.13	11.16
33	Providence No.1 and 9 Seam,Ky-33	13.72	0.48	1.22	5.20	0.56	8.75	34.47	11.78	0.38	37.45
34	Kite-Elkhorn 1	8.95	0.64	3.14	6.10	1.45	21.67	46.49	6.27	0.18	14.29
35	Welco-Elkhorn 3	22.60	0.31	1.53	2.15	0.54	46.69	53.03	1.95	0.66	16.32
36	Lyons, Va.	8.57	0.51	2.13	1.69	0.75	13.95	38.32	12.06	0.35	30.42
37	Splash Dam,Va.-37	14.41	1.15	2.92	3.29	1.67	16.55	45.08	11.78	0.12	17.77
38											
39	Texas Lignite	13.74	0.49	0.49	13.69	2.69	10.80	48.83	5.88	0.83	16.27
			0.45	0.77	1.24	0.39	6.95	27.98	11.98	0.57	50.13
			0.58	0.78	1.17	0.38	7.19	28.91	12.20	0.53	48.54
			0.57	0.92	1.16	0.42	9.19	33.18	10.32	0.49	43.91
			0.88	0.04	1.88	0.33	0.62	0.91	0.91	0.13	94.44

CONVERSION FACTORS

0.1 Lbs NO_x (as NO_2) Per 10^6 Btu = 43 Nanogram Per Joule

10^6 Btu Per Hour = 0.293 Megawatts Thermal (MW_t)

$[T(^{o}F) + 460] \times \frac{5}{9} = T(K)$

1 Inch = 2.54 cm

2.2 Lb = 1 kg